AN ANALYSIS OF BIOENERGY CROPPING SYSTEMS IN THE NORTH-CENTRAL UNITED STATES

By

Katherine Elizabeth Hadley

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

Crop and Soil Sciences - Master of Science

2014

ABSTRACT

AN ANALYSIS OF BIOENERGY CROPPING SYSTEMS
IN THE NORTH-CENTRAL UNITED STATES

By

Katherine Elizabeth Hadley

Recent U.S. Energy Policy such as the Renewable Fuels Standard has been created to reduce our dependence on fossil fuels and mitigate global climate change. The GLBRC Bioenergy Cropping Experiment contains annual cropping systems and perennial cropping systems. Field inputs, gas emissions, and yields have been tracked since establishment in 2008. Field data was used to perform a life cycle assessment on these cropping systems with a focus on the global warming potential (GWP). The results of the LCA showed that the continuous corn cropping systems had the highest GWP per hectare per year at both locations. The perennial systems generally had a negative GWP per hectare per year due to limited inputs and gas emissions. Material inputs that contributed most to GWP were synthetic nitrogen fertilizers. Nitrous oxide emissions had the greatest effect on the GWP of each system of all of the gas emissions considered. The second chapter of this thesis research focused on a successful and cost effective establishment method for switchgrass. Switchgrass is an herbaceous perennial grass capable of producing large amounts of biomass. Biomass can be converted to cellulosic ethanol. Stand establishment to maximum biomass potential required several years. A field experiment was conducted to identify if a double crop management system was possible for switchgrass establishment. The results of the experiment showed that August seeded switchgrass could not be successfully established following a wheat crop. June seeded switchgrass after a rye crop and fallow (control treatment) were successfully established. No significant differences in stand establishment or yields were seen between these two treatments.

ACKNOWLEDGEMENTS

Special thanks to Dr. Kurt Thelen for providing me with a great learning experience and the framework and guidance for this project. I was fortunate enough to have Dr. Karen Renner and Dr. Steve Hamilton serve as my committee members. Thank you for your time and for your input and suggestions to make this thesis better.

Thank you to all of the wonderful MSU staff and students who I got to meet along my journey - Pavani Tumbalam, Andrew Adkins, Randy Laurenz, Casey Reagan, Bill Widdicombe, Lori Williams, Todd Martin, and Sichao Wang.

A big shout out to Kaite Hard, my partner in crime and other half of the 'Kates'! I couldn't have gotten through grad school without you!

I would also like to thank my parents, friends, and Sigma Alpha sisters who believed in me and who have supported me throughout my life and this project.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

LIFE-CYCLE ASSESSMENT OF THE GREAT LAKES BIOENERGY CENTER'S BIOENERGY CROPPING SYSTEM EXPERIMENT

ABSTRACT

Recent legislation such as the Renewable Fuels has been created to reduce our dependence on fossil fuels and mitigate global climate change. The GLBRC Bioenergy Cropping Experiment, established in 2008 at UW-Madison and MSU, contains annual cropping systems (corn, soybeans, canola) and perennial cropping systems (switchgrass, miscanthus, a native grass mix, old field, poplar, a prairie grass mix). Field inputs, gas emissions, and yields have been tracked since establishment. This field data was used to perform a life cycle assessment on these cropping systems with a focus on the global warming potential (GWP). The results of the LCA showed that the continuous corn cropping systems had the highest GWP per hectare per year at both study locations as expected. The net GWP of a cropping system was heavily influenced by the nitrous oxide emissions for that system. A statistical analysis revealed no significant differences between locations for each cropping system (Student's t-test) or between cropping systems at each location (ANOVA) likely due to the large variations in annual nitrous oxide emissions. The perennial systems generally had a negative GWP per hectare per year due to limited inputs and gas emissions from those systems. The material inputs that contributed most to GWP were synthetic nitrogen fertilizers. Nitrous oxide emissions had the greatest effect on the GWP of each cropping system of all of the gas emissions considered.

INTRODUCTION

Renewable Fuels

The Energy Independence and Security Act (EISA) of 2007 was an act created and passed by the US government in order to increase energy security and to promote energy independence. Part of the EISA included revisions and updates to the Renewable Fuels Standard (RFS) program. The RFS already included framework for developing biofuels as an alternative fuel source to reduce greenhouse gas (GHG) emissions and mitigate global climate change (Menten et al, 2013). The newly revised program, referred to as RFS2, redefined the criteria for renewable fuels and set volume requirements for use as transportation fuels each year. The RFS2 requires the amount of renewable fuels produced in the US to increase each year leading up to 36 billion gallons per year (BGY) in 2022 (US Department of Energy, 2011). In addition to the total volume requirements, RFS2 outlines specific fuel source requirements: 16 BGY of cellulosic biofuels, 14BGY of advanced fuels, 1 BGY of biomass-based biodiesel, and 15 BGY of conventional biofuels (US Department of Energy 2011). The new definition of renewable fuels also includes criteria for greenhouse gas emission reduction thresholds.

Starch-based ethanol and biodiesel are conventional biofuels, also called first generation biofuels, and are the primary liquid transportation biofuels available in the US. Currently, over 95% of the ethanol produced in the US is from corn grain (*Zea mays*) (Drapcho, 2008). Biodiesel production has traditionally used soybeans (*Glycine max*) as the main feedstock source. In 2007, 83% of biodiesel was soybean biodiesel (US Department of Energy, 2011). Other oil seed crops, such as canola (*Brassica napus*) or sunflowers (*Helianthus annuus*), are also used as biodiesel feedstocks, but to a much lesser extent.

From a sustainability standpoint, first generation biofuels present two major challenges: large agronomic input requirements during the production phase and land use concerns. Conventional commodity cropping systems use many agronomic inputs including high rates of commercial fertilizers. The production and use of fertilizers significantly contribute to the environmental impacts of a cropping system because of the raw material extraction and energy use required for their production (Skowroñska, 2014). Future cropping systems will have to become more efficient in their use of agronomic inputs to be sustainable in the long term. Sustainable production is necessary because biofuels produced from conventional sources are required to reduce GHG emissions by 20% as compared to the lifecycle GHG emissions of the 2005 baseline average gasoline or diesel fuel that it replaces to be considered renewable fuels under the RFS2 definition (Congressional Research Service, 2013). Using arable land for biofuel feedstock production instead of food production has been a source of controversy for policymakers. In 2010, 38% of corn grain produced in the US was used for ethanol production, totaling 13.2 billion gallons of ethanol and 39 million metric tons of dry distiller grains (US Department of Energy, 2011; ethanolrfa.org, 2014). Dry distiller grains (DDG) are an important co-product of ethanol production and are used as a high quality livestock feed. According to the Renewable Fuels Association, nearly one-third of the corn grain used for ethanol production is not removed from the food market. Demand has grown for ethanol in the US due to increased gasoline blend requirements (E-15) and the introduction of Fuel Flex vehicles (E-85). As the corn grain ethanol market continues to expand, food vs. fuel becomes a concern due to biofuels feedstock production taking acres away from food production. With the world's population expected to increase to 9+ billion people by 2050, food production will have to increase 50-80% during the same time period (Brentrup, 2008).

Cellulosic derived ethanol, a second generation biofuel, has been proposed as a viable alternative to using traditional food crops as biofuel feedstocks. Cellulosic ethanol is produced by breaking down lignocellulos in plant biomass to simple sugars, mainly glucose and xylose. The simple sugars are fermented into ethanol. Feedstocks for cellulosic ethanol have been in development since 1976 when the US Department initially funded research programs to identify high-yielding herbaceous biomass crops (Wright, 2007). In 1991, switchgrass (*Panicum virgatum*) was identified as a 'model' bioenergy crop (US Department of Energy, 2011). Since the early 1990's various other grass and woody species have been identified as potential bioenergy feedstocks as well.

The purpose of cellulosic derived ethanol is that it has the potential to alleviate the sustainability concerns caused by first generation biofuels. Dedicated bioenergy crops are not food crops. To further reduce food vs. fuel concerns, cellulosic feedstocks have been bred to be grown on marginal lands where sustainable food production is unlikely or impossible. Many cellulosic bioenergy crops do not require large amounts of agronomic inputs, such as fertilizers or herbicides, although these requirements vary by crop. High-yielding, low input biomass systems can potentially make cellulosic ethanol able to meet the RFS2 GHG emission reduction threshold of a 60% reduction as compared to the lifecycle GHG emissions of the 2005 baseline average gasoline or diesel fuel that it replaces (Congressional Research Service, 2013).

Any biofuel that is not corn starch-based qualifies as an advanced biofuel under the RFS2. Advanced biofuels can come from grain (other than corn), cellulosic sources (including

corn stover), and biomass based biodiesel (Congressional Research Service, 2013). The inclusion of advance biofuels in the RFS2 requirements bridge the gap between first generation biofuels and second generation biofuels and allow for a transition period while technologies and infrastructure are developed for cellulosic biofuels. Advanced biofuels also allow for a mandated GHG emission reduction threshold during the transition period - a 50% reduction as compared to the lifecycle GHG emissions of the 2005 baseline
average gasoline or diesel fuel that it replaces (Congressional Research Service, 2013).

Life Cycle Assessment

Life cycle assessment (LCA) is a decision making tool used to assess environmental impacts of a product or system. Historically, LCA has been used in the packaging and manufacturing industries where material inputs are readily calculated and factory and process emissions can be easily identified and quantified for each life cycle stage. Due to the overwhelming success of LCA studies in these industries, LCA work has expanded into other applications such as agricultural systems. The first biofuel LCA was published by Kaltschmitt et al in 1997 and focused on first generation biofuels. After that initial study, LCA had become an accepted and highly used approach to study environmental impacts, including GHG emissions of biofuels (Menten et al, 2013).

During a life cycle assessment, the entire life cycle of a system is broken down into all of its life stages starting with the 'cradle', extraction of resources, to the 'grave', end of life. Each life cycle stage is examined and weak stages can be identified. The principles and framework for life cycle assessment are defined in ISO 14040:2006 with additional requirements and guidelines defined in ISO 14044:2006. A complete LCA is composed of four main phases: (1) goal and scope definition, (2) life cycle inventory, (3) life cycle impact assessment, and (4) life cycle interpretation. LCA phases are interconnected as shown in Figure 1.

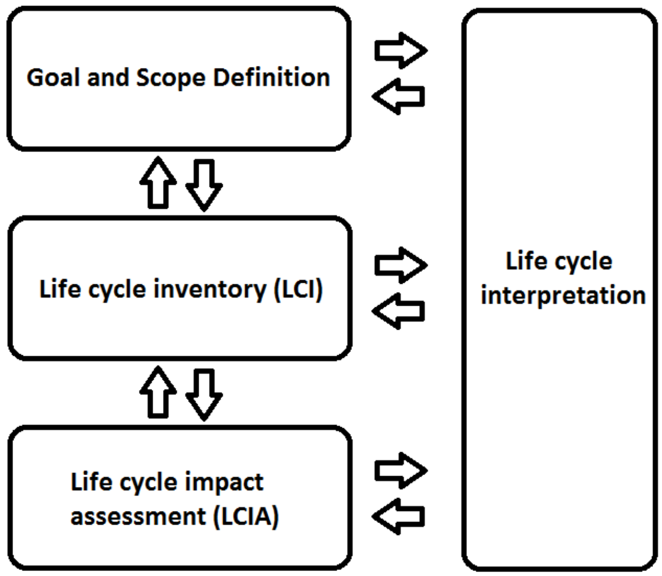


Figure 1. A visual depiction of life cycle assessment.

Other than the general guidelines and requirements outlined in ISO standards, there is no standardized methodology for conducting life cycle assessments. The lack of standardization in LCA makes it hard to compare results of one study to another. Agriculture LCAs also face a unique set of challenges that cause a great deal of variation and uncertainty in the results (Kendall et al, 2013). Obvious differences such as climate, soil type and health, and management practices vary greatly by region and can have a major impact on the agronomic inputs and yields of cropping systems. Many biofuel LCAs rely on data from computer simulated cropping systems such as the CERES-EGC model to estimate crop yields and environmental emissions for their life cycle inventory (LCI) (Bessou, 2012). Very few LCAs review used field data and/or field measured gas fluxes in their life cycle inventories. The use of experimentally determined field data can improve the data quality component of the LCI in cropping system LCAs and tailor results to specific geographic regions and management practices.

The type of LCA and other LCA methodology choices will also impact the results of a study. There are two types of LCAs, attributional and consequential. LCAs have traditionally been conducted as attributional LCAs. Usually retrospective, this method simply evaluates the inputs and outputs of life cycle and identifies areas of greatest potential environmental impact. Consequential LCAs are usually prospective and consider changes to a life cycle in order to reduce potential environmental impacts. Consequential LCAs also consider direct and indirect impacts of changing the life cycle (Kendall et al, 2013). The effects of indirect land use changes are especially important to biofuel production but are hard to study even with consequential LCAs. Consequential LCAs require significantly more time, and resources, and are more costly, yet still can have high levels of variability and uncertainty due to direct and indirect system changes. The LCA conducted in this research will be a retrospective attributional LCA and will not account for land use changes cause by dedicated biofuel crops replacing food crops on arable land in the study locations.

Functional unit choice has been shown to significantly impact the results of a biofuel LCA (Caffrey, 2012). The functional unit is a measure of the intended function for the system. Biofuel LCAs commonly use one of three functional units: energy (ie. MJ of energy), land area (ie. hectare of land), or mass (ie. kg of corn grain). Mass based functional units are used when comparing systems with the exact same product; for example comparing switchgrass harvest strategies would use a function unit of kilograms of dry switchgrass biomass. Energy functional units are useful when comparing feedstocks that produce different products; for example comparing corn grain ethanol to soybean biodiesel might use a functional unit of MJ of energy. Land area functional units are used when the intensity of cropping systems is to be compared (Skowronska et al, 2014). A land area functional unit will be primarily utilized in the LCA conducted in this research. Using a land area functional unit also increases the practicality of the research in terms of the future bioenergy feedstock considerations from the results.

GLBRC Biofuels Cropping Experiment

The Great Lakes Bioenergy Research Center (GLBRC) is one of three bioenergy research centers created and funded for five years by the US Department of Energy (DOE) in 2007. In 2013, funding was extended for an additional five years. The GLBRC mission statement is as follows: “to perform the basic research that generates technology to convert cellulosic biomass to ethanol and other advanced biofuels.” (GLBRC, 2014). The GLBRC is broken down into four main areas of research Area 1: Plants, Area 2: Deconstruction, Area 3: Conversion, and Area 4: Sustainability. Each area is further divided into specific areas of interest. Through collaboration between research areas, large-scale research is made possible. One such large-scale research effort is the GLBRC Biofuels Cropping System Experiment.

The goal of the GLBRC Biofuels Cropping System Experiment is to model the production efficiencies of novel bioenergy crop production systems. The experiment includes “assessing crop yield and quality, microbial-plant interactions, biogeochemical responses, water needs, greenhouse gas fluxes, nutrient leaching to groundwater, biodiversity responses and socioeconomic impacts” (GLRBC, 2014).

Objective

The objective of this research is to perform an attributional life-cycle assessment to evaluate the global warming potential of the production phase the main plot treatment cropping systems located in the GLBRC Biofuels Cropping Experiment. The life-cycle inventory will primarily consist of the actual field data acquired between experiment establishment in 2008 and the end of the growing season in 2012. Field data includes material inputs and non-material inputs. Experimentally derived nitrous oxide (N_2O) gas flux data will also be used in the life-cycle inventory. Life-cycle assessment software GaBi 6.0 (P.E. International) will be used to create representative models of each cropping system.

MATERIALS AND METHODS

Field Experiment

The GLBRC Biofuels Cropping System Experiment intensive sites were established in 2008 at the Arlington Agricultural Research Station (ARL) (43°18’10.2”N, 89°20’43.0” W) in Arlington, Wisconsin with a second location at Kellogg Biological Station (KBS) (42°24’19”N, 85°24’04”W) in Hickory Corners, Michigan. The experimental design is randomized complete block design with five blocks. The experiment has ten cropping system treatments. Plots are approximately 40 meters long by 28 meters wide with an area of 0.12 hectares. Field layouts are shown in Figures 1 and 2. Prior to experiment establishment in 2008, alfalfa was grown on the entire KBS site and on blocks 1, 2, and 3 at ARL. Blocks 4 and 5 at ARL had corn as the previous crop. Field activities from both locations have been carefully tracked and recorded for each system since establishment in 2008.

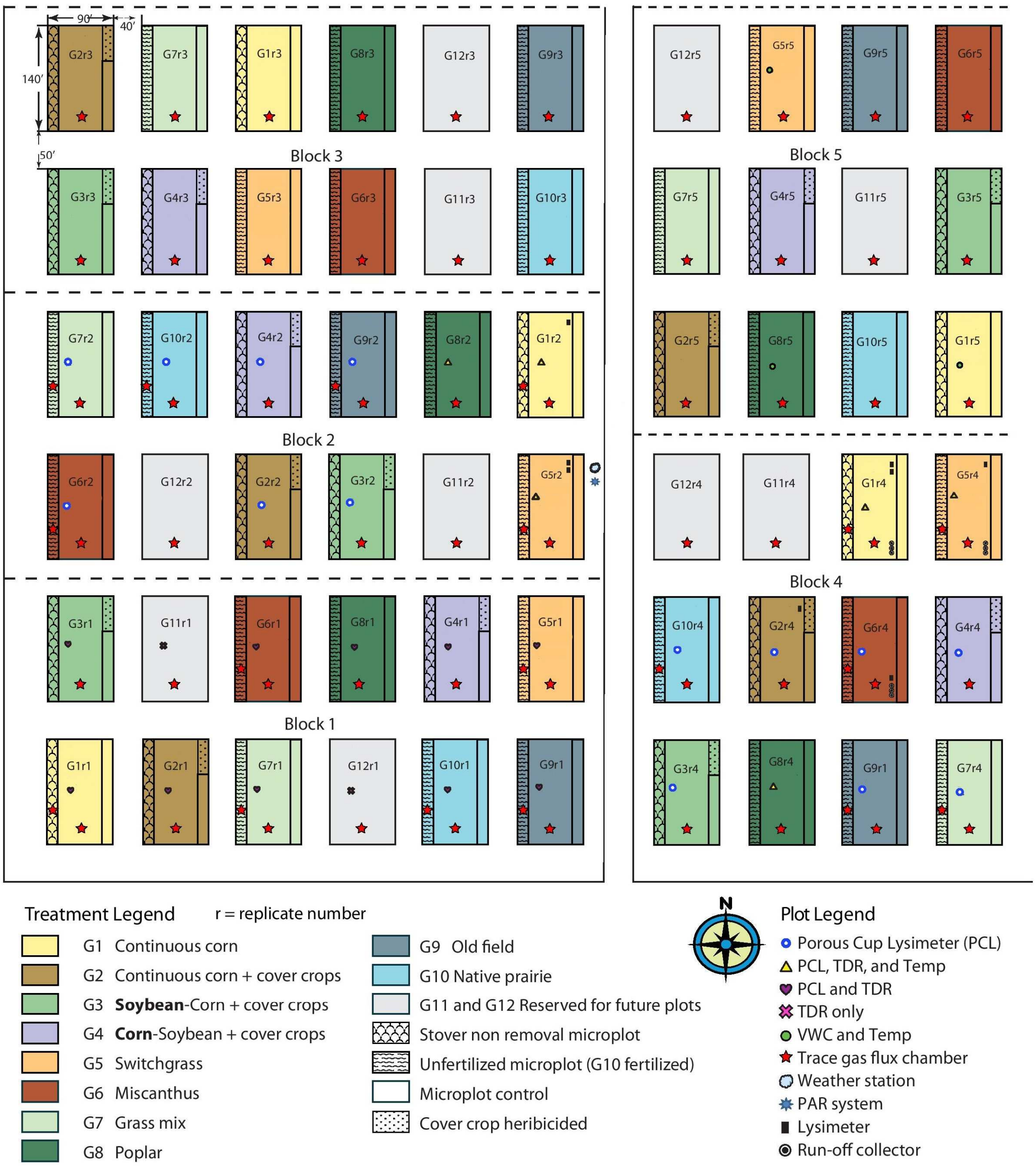


Figure 2. Arlighton Argicultural Research Station plot map.

Figure 3. Kellogg Biological Station plot map.

Main Plot Treatments

Annual Cropping System Treatments

Table 1. Annual cropping system crops by year. Variety information is included in the appendix.

Year	Treatment	Treatment Name	Crop
2008	G1	Continuous Corn	corn
2009			
2010			
2011			
2012			
2008	G2	Corn-Soybean-Canola rotation	corn
2009			soybean
2010			canola
2011			corn
2012		Continuous Corn + cover crops	corn
2008	G3	Corn-Soybean-Canola rotation	soybean
2009			canola
2010			corn
2011			soybean
2012		Corn-Soybean rotation + cover crops	corn
2008	G4	Corn-Soybean-Canola rotation	canola
2009			corn
2010			soybean
2011			canola
2012		Corn-Soybean rotation + cover crops	soybean

Perennial Cropping System Treatments

Table 2. Perennial cropping system crops by year.

System	System Name	Group		Species (*latin*)	Common Name / Variety
G5	Switchgrass	Graminoids	C_4	*Panicum virgatum*	switchgrass / Cave-in-rock
G6	Miscanthus	Graminoids	C_4	*Miscanthus x giganteus*	giant miscanthus
G7	Native Grass Mix	Graminoids	C_3	*Elymus canadensis*	Canada wildrye
			C_4	*Panicum virgatum*	switchgrass
				Andropogon gerardii	big bluestem
				Schizachyrium scoparium	little bluestem
				Sorghastrum nutans	Indiangrass
G8	Hybrid Poplar			*Populus nigra x P. maximowiczii*	Hybrid poplar / NM6
G10	Prairie Grass Mix	Graminoids	C_3	*Koeleria cristata*	prairie Junegrass
				Elymus canadensis	Canada wildrye
			C_4	*Panicum virgatum*	switchgrass
				Andropogon gerardii	big bluestem
				Schizachyrium scoparium	little bluestem
				Sorghastrum nutans	Indiangrass
		Legumes		*Desmodium canadense*	showy ticktrefoil
				Lespedeza capitata	roundhead lespedeza
				Baptisia leucantha	white false indigo
		Early forbs		*Rudbeckia hirta*	blackeyed Susan
				Anemone canadensis	Canadian anemone
				Asclepias tuberose	butterfly milkweed
		Mid forbs		*Silphium perfoliatum*	cup plant
				Monarda fistulosa	wild bergamot
				Ratibida pinnata	pinnate prairie coneflower
		Late forbs		*Solidago rigida*	rigid goldenrod
				Solidago speciosa	showy goldenrod
				Aster novae-angliae	New England aster

Treatment Descriptions

G1 - Continuous Corn

Continuous corn is a common system in the Midwestern United States. The purpose of this treatment is to represent an annual high-input cropping system and act as a basis for comparison with other systems.

G2 - Continuous Corn + Cover Crops

In the 2012 growing season, the canola phase was eliminated from the experiment because canola isn't a widely grown crop the Midwest. The change from a corn-soybean-canola rotation to a corn-soybean rotation better reflects current cropping practices in the region. To replace the rotation, an annual conventional corn with cover crops system was added. Conventional corn with cover crops will provide a comparison for treatment G1. Cover crops provide cover during winter months reducing erosion and can provide nitrogen credits to the system if legumes such as red clover are used as cover crops.

G2 - Corn - Soybean - Canola rotation / G3 - Soybean - Canola - Corn rotation / G4 - Canola - Corn - Soybean rotation

Treatments G2, G3, and G4 had the same annual corn-soybean-canola rotation systems in 2008, 2009, 2010, and 2011, but each treatments represents a different entry point of the rotation. The purpose of this is to have one treatment of corn in rotation, one treatment of soybeans in rotation and one treatment of canola in rotation each study year. The introduction of canola into the basic corn-soybean rotation increases the biodiversity of the rotation, and if winter canola varieties are used can provide vegetative cover during winter months to reduce erosion. Canola biodiesel has a lower gel temperature than soybean biodiesel which can make canola biodiesel favorable in cold environments.

G3 - Corn-Soybean Rotation + Cover Crops / G4 - Soybean-Corn Rotation + Cover Crops

The canola phase was removed in 2012 and future experiment years to accommodate the implementation of the cover crop systems. An annual corn-soybean rotation is more common than corn-soybean-canola rotation in the Midwestern US and therefore the new treatment is a better representation of cropping systems found in the region. Cover crops were also included in this treatment for the same reasons listed above.

G5 - Switchgrass

Switchgrass was identified by the US DOE as a 'model' bioenergy crop in 1991 and is still considered a bioenergy feedstock of major importance (US Department of Energy, 2011). Native to the US, switchgrass is a perennial grass capable of producing up to 10 tons of biomass per acre in northern climates (MSU Extension, 2007). Switchgrass is direct seeded. Issues can arise with hard seed, so seeding rates are generally inflated to ensure even stand emergence (Hedtcke et al, 2014). Stand establishment can take 2-3 years to reach peak biomass yields. A first year biomass harvest is not recommended and could affect the overwintering ability of the stand. First year management generally includes weed control (herbicide or mowing) but no fertilizer application. Management in subsequent years requires only fertilizer application, specifically nitrogen. Switchgrass can be used for cellulosic ethanol or co-fired with coal.

G6 - Miscanthus

Giant miscanthus (*Miscanthus x giganteus*) is a cross between *Miscanthus sinensis* and *Miscanthus sacchariflorus* and is a prime example of hybrid vigor. Giant miscanthus produces more biomass than either of its parents and is sterile. Miscanthus must be propagated by rhizome which reduces concerns of it becoming an invasive species. Miscanthus is a perennial crop capable of producing large amounts of biomass with yields reaching 10-15 tons per acre in northern climates (MSU Extension, 2007). Stand establishment may take several years to reach peak biomass. A first year biomass harvest is not recommended and could affect the overwintering ability of the stand. First year management generally includes weed control (herbicide or mowing) but no fertilizer application. Management in subsequent years requires only fertilizer application, specifically nitrogen. Although miscanthus is a viable feedstock for cellulosic ethanol, the relatively high lignin content makes it a better direct combustion fuel source with current conversion technologies.

G7 - Native Grass mix

The Native Grass mix contains five perennial grass species native to the US. See Table 2 for complete species list. The purpose of G7 is to serve as an intermediate between the highly diverse G10 system and the monoculture G5 switchgrass system. Biomass harvested at the end of each season could theoretically be used for cellulosic ethanol production.

G8 - Hybrid Poplar

Hybrid poplar is a fast growing tree species and is the only woody species included in this cropping experiment. Hybrid poplar is also the only crop in this experiment that is not harvested each year. Hybrid poplar is vegetatively propagated by cuttings called whips. Predation by animals and weed competition can be an issue during the initial establishment phase and must be controlled to ensure even stand establishment. Hybrid poplar can be used as a cellulosic feedstock however the moderately high lignin content makes conversion under current technologies not ideal. Genetically modified hybrid poplar varieties with reduced lignin contents are currently in development.

G9 - Old Field

As opposed to the high-input continuous corn G1 treatment, the old-field treatment is the low-input treatment in this experiment used for comparison with other systems. The old-field treatment was tilled at establishment (as was every treatment) in 2008 but nothing was planted. Whatever seeds were present in the soil seed bank were able to germinate and grow unregulated. The Old-field treatment is considered a perennial treatment because the seed bank and essentially the weeds in the plots produce seed to grow the next years 'crop'. This treatment received annual nitrogen application so it cannot be considered an untreated control. Biomass harvested at the end of each season could theoretically be used for cellulosic ethanol production.

G10 - Native Prairie

The Native Prairie treatment is the high-diversity, low input (HDLI) treatment in this experiment. This treatment contains a perennial mixture of six grasses, three legumes, three early forbs, three mid forbs and three late forbs. See Table 2 for complete species list. All of the species in this treatment are native to the US and would have been found naturally across the

Midwestern prairies before production agriculture. This treatment did not receive supplemental nitrogen fertilizer. Biomass harvested at the end of each season could theoretically be used for cellulosic ethanol production.

Goal and Scope Definition

Goal

The goal of this research was to conduct an attributional life-cycle assessment (LCA) to identify and compare the global warming potential of the main plot treatment in each cropping systems in the GLBRC Biofuels Cropping Experiment on a land area basis. The functional unit is one hectare of arable land per year. Systems with the lowest environmental impacts, specifically, the lowest global warming potential, will be highlighted for future research.

Temporal and Geographic Scopes

The time frame for this research is from experiment establishment in the spring of 2008 through harvest in 2012.

Experimental locations were located in the north central US, therefore management practices and the grain and biomass yields are reflective of the climate and soil conditions of the region. During the study years, the average annual temperature was 6.8°C and average annual precipitation was 913 mm at the ARL location (National Weather Service, 2014). The average annual temperature was 9.2°C and average annual precipitation was 878 mm at the KBS location (MSU Enviro-weather, 2014). Plano silt-loam (Family: Fine-silty, Mixed, Superactive, Mesic Typic Argiudolls) is main soil series present at the ARL experiment site. This soil was formed under prairie vegetation in loess deposits over calcareous glacial till and contained 3.8% soil organic matter (SOM). The drainage class of this soil is well drained. Kalamazoo loam (Family: Fine-Loamy, Mixed, Semiactive, Mesic Typic Hapludalfs) is the main soil series present at the KBS experiment site. This soil was formed under forest vegetation in loamy outwash overlaying sand and gravel and contained 2.4% SOM. The drainage class of this soil is well drained. Soil information is from an unpublished manuscript from Gregg Sanford at the University of Wisconsin – Madison.

Hybrid poplar, treatment G8, was intentionally left out of this study. Hybrid poplar was established when the experiment began 2008 but was not completely harvested within the timeframe of this study. Hybrid poplar was harvested in late 2012 at ARL and early 2013 at KBS.

System Boundary

Because the goal of this study is specific to the cropping system phase of biofuel feedstock production, the system boundary will be cradle-to-field gate. Using cradle as the starting point of this study ensured that the extraction and production of agronomic inputs was considered. However, the labor in man hours and all other factors pertaining to the farm workers, including but not limited to transportation to work, calories consumed, human health index, were not considered in this study. Field gate is the point at which crops were harvested from the field but have not left the field or been transported away from the field. Transportation to storage facilities on the farm, grain elevators, biomass processing facilities, or bio-refineries is outside of the system boundary for this study because it is dependent on the type of feedstock harvested (grain or biomass). Differences in feedstock transportation should be considered in life-cycle assessments where conversion is the end point in the system boundary (ie. not this study).

Co-Products and Allocation

Identification of co-product allocation procedures in LCAs is required by the ISO standards. Due to the complex nature of agricultural systems, allocation procedures are rarely consistent between studies and are at the discretion of the researcher. In this study, the only co-product was the crop residue returned to the soil after grain and biomass harvest. Crop residue from the previous year was considered part of the soil due to cropping system modeling limitations imposed by the LCA software. Crop nutrition requirements were calculated based on soil sampling each year and therefore included nutrients returned to the soil from the previous crops residue. A similar approach was used by Bessou et al. 2012 for modeling sugar beet cropping systems.

Life Cycle Inventory (LCI)

The life cycle inventory (LCI) for the LCA used as much experimentally derived data as possible. Experimentally derived data comes from the field data and observed gas fluxes from the GLBRC Biofuel Cropping System Experiment. Field data including but not limited to: material inputs, field operations, and yield data from each location, was carefully tracked and recorded since experiment establishment. With authorization, field data logs can be accessed at data.sustainability.glbrc.org under the heading 'GLBRC Biofuel Cropping System Experiment'.

General Management Practices

Crop management decisions were based on best management practices and Extension recommendations for each location and were dependent on local climate and soil properties. Nitrogen rates for corn systems were calculated using the Maximum Return to Nitrogen tool and depended on soil type, previous crop, yield expectation, nitrogen cost, and corn price. Annual crop variety information can be found in Table 6 of the Appendix. Soil tests were conducted at the beginning of each growing season and together with rotation sequence (in the annual cropping systems) were used to determine fertilizer requirements each year. Soil pH was adjusted in all plots with dolomitic lime prior to experiment establishment at ARL. Based on soil test results, pH adjustment was not required at KBS.

Tillage operations were performed only in 2008 at experiment establishment on all plots. Tillage was more extensive at ARL than KBS. At ARL, a chisel plough was used as primary tillage. During secondary tillage plots were disked, field cultivated and culti-packed. At KBS, secondary tillage from a soil finisher was the only tillage operation. No-till planting and management practices were used in subsequent years for all of the annual treatments.

Production scale equipment was used to harvest all crops. Corn and soybean harvest occurred after physiological maturity (black layer in corn, 95% of pods reached full color in soybeans) and when the grain reached optimum moisture content for grain quality and safe storage. Canola was swathed at 60% seed color change and then combined five to fourteen days later. Perennial crops were harvested within two weeks of the first killing frost (-3°C) of the fall. At ARL, perennial crops were windrowed then chopped with a self-propelled forage harvester. At KBS, perennial crops were direct chopped with a self-propelled forage harvester. All perennial crops were cut a 15 cm stubble height.

Table 3 presents an overview of the management practices and inputs used in each cropping system by location. The solid grey color indicates the systems received that particular input.

Table 3. An overview of the management practices and inputs used in each cropping system by location. The solid grey color indicates the systems received the input indicated in the first column.

System	G1 / corn-rot		Soybean-rot		Canola-rot		G5		G6		G7		G9		G10	
Crop	Corn		Soybean		Canola		Switchgrass		Miscanthus		Native Grass Mix		Old Field		Prairie Grass Mix	
Location	ARL	KBS	ARL	KBS	ARL	KBS	ARL	KBS	ARL	KBS	ARL	KBS	ARL	KBS	ARL	KBS
Average Seeding Rate (ha^{-1})	84,000 sds	70,900 sds	432,000 sds	444,800 sds	6.46 kg	11.34 kg	7.6 kg		17,200 rhizomes	16,714 rhizomes	8.9 kg		0 kg		8.5 kg	
Row Spacing	76 cm		38 cm		19 cm											
Ammonium Polyphosphate (10-34-0)																
Monoammonium Phosphate (11-52-0)																
Custom Starter (5-14-42)																
Urea Ammonium Nitrate (28-0-0)																
Ammonium Nitrate (34-0-0)																
Urea (46-0-0)																
Potash (0-0-60)																
Weed Control																

LCI Calculation

Treatments G1, G5, G6, G7, G9, G10

Each material input was averaged across the five treatment years to come up with one representative value to plug into the cropping system models. Field data used Imperial measurement units so everything was converted to metric units as well (ie. kg, ha). For example, G1-Continuous Corn at KBS was planted at 28,000 seeds acre^{-1} in 2008, 28,000 seeds acre^{-1} in 2009, 28,000 seeds acre^{-1} in 2010, 29,300 seeds acre^{-1} in 2011, and 30,200 seeds acre^{-1} in 2012. The value for corn seed in the G1-Continuous Corn at KBS model is 20.05 kg.

$$(28{,}000 + 28{,}000 + 28{,}000 + 29{,}300 + 30{,}200) \div 5 \text{ years} = 28{,}700 \text{ seeds acre}^{-1}$$

$$28{,}700 \frac{\text{seeds}}{\text{acre}} \times \frac{1}{0.404686} \frac{\text{acre}}{\text{hectare}} = 70{,}919 \text{ seeds hectare}^{-1}$$

$$\left((70{,}919 \times 56 \frac{\text{lbs}}{\text{bu}}) \div 90{,}000 \frac{\text{seeds}}{\text{bu}}\right) \times \frac{1}{2.2} \frac{\text{kg}}{\text{lbs}} = 20.05 \text{ kg hectare}^{-1}$$

A complete list of material input values used in the cropping system models is located in Appendix Table 16 for ARL and Appendix Table 10 for KBS. Estimated diesel use was calculated for each piece of equipment based on equipment type and horsepower using the MSU Extension Custom Machine and Work Rate Estimates for 2013. A complete list of equipment used can be found in Appendix Table ##.

Non-material inputs included all field operations, tillage, planting, fertilizing, weed control (spraying), and harvesting, and arable land (recall, 1 ha year^{-1} is the functional unit). Non-material inputs were averaged across the five treatment years to come up with one representative value to plug into the cropping system models the same way as the material input values were calculated. A complete list of non-material input values used in the cropping system models is located in Appendix Table 17 for ARL and Appendix Table 11 for KBS.

Yields were also averaged across the five treatment years. The average corn grain yield in Mg was calculated for G1-Continuous Corn. Stover was not considered in this study. Mg of dry matter biomass was used for the perennial treatments. Treatments were primarily studied and compared based on a land area basis (1 ha year^{-1}), however, treatment yields were converted to predicted biofuel energy in MJ and compared on a per energy basis. The purpose of this was to show that functional unit choice would significantly impact the results of the LCA. To convert yields (Mg) to energy (MJ), equations [1], [2], [3], and [4] in the Appendix were used. Continuous corn produced the greatest amount of energy (in MJ) at each location and set to a factor of 1. The other treatment cropping system models were scaled appropriately based on their estimated energy production in MJ compared to the continuous corn treatment.

Rotational Treatments G2, G3, G4

Rotational treatment material and non-material input model values were calculated in much of the same way as the other treatment model values. The difference was that the rotational systems were separated into models for each crop in the rotation. Corn in rotation (corn-rot) was an average of six treatment years: G2-2008, G2-2011, G2-2012, G3-2010, G3-2012, and G4-2009. Soybeans in rotation (soybean-rot) was an average of five treatment years: G2-2009, G3-2008, G3-2011, G4-2010, and G4-2012. Canola in rotation (canola-rot) was an average of four treatment years: G2-2010, G3-2009, G4-2008, and G4-2011.

A rotational system model was also created: the corn-rot values were multiplied by six (treatment years), the soybean-rot values were multiplied by five, and the canola-rot values were multiplied by four. Each input value was summed and then divided by fifteen treatment years.

Material and non-material input values for the corn-rot, soybean-rot, canola-rot, and the rotational system cropping system models for each location are also located in Appendix Tables 10, 11, 16, and 17.

Greenhouse Gas Fluxes

Carbon dioxide, nitrous oxide and methane are the major greenhouse gases that contribute to global warming. Methane emissions from cropping systems have been proven to have an insignificant affect on global warming potential compared to carbon dioxide and nitrous oxide (Bessou et al. 2012, Menten et al. 2013, Skowronska et al. 2014). For this reason, the methane gas fluxes of the cropping systems were not considered in this study.

All of the treatments in this study except for treatment G10 and the soybean phase of the rotation systems received nitrogen fertilizer applications. Nitrous oxide is naturally produced in soils during nitrification and de-nitrification (Huang, 2014). However, the most important nitrogen emission is nitrous oxide (N_2O) in terms of global warming potential because of its radiative effect in the atmosphere. One kg of nitrous oxide has the effect of 298 kg of carbon dioxide on global warming potential. Global warming potential is expressed in units of carbon dioxide equivalents (CO_2-equiv, CO_2-e). Studying nitrous oxide gas fluxes will help researchers evaluate options for emission mitigation through management practice changes and/or policy intervention. Nitrous oxide emissions from the cropping systems were experimentally determined by the GLBRC Area 4.3 Biogeochemical Research Group.

Estimating N_2O emissions

The N_2O emission estimation protocol is an excerpt from Oates et al. (unpublished 2004). "While soil temperatures were consistently > 0 C, nitrous oxide (N2O) fluxes were measured twice monthly, as well as immediately following precipitation events (Robertson et al., 2000) using vented static chambers (Livingston & Hutchinson, 1994). The chambers had a 28.45 cm diameter and 18 cm headspace height and were inserted 5 cm below the soil surface. Chamber lids were modified with a septum for gas extraction and a vent to allow for chamber pressure equilibration. Tubing was attached to the vent prior to capping and hung inside the chamber to reduce possible crosswind induced loss of gas from the chamber vent. Headspace gas from within the chambers was extracted immediately following lid placement with a 30 mL nylon syringe and a 23-gauge needle. Three subsequent extractions were made at 20-min intervals over a 60-min period. Glass 5.9 mL Exetainer vials (Labco Limited, Buckinghamshire, UK) were flushed with 20 mL of extracted sample and then overcharged with 10 mL of sample to facilitate sample extraction for analysis (Parkin & Venterea, 2010). Field standards (1 ppm N2O) and ambient air were also loaded into vials at this time to assess ambient GHG concentrations and potential storage-vial degradation in the period between sampling and analysis. Samples were analyzed by gas chromatography using an electron capture detector (micro-ECD, Agilent 7890A GC System, Santa Clara, CA, USA).

"Carbon dioxide (CO_2) accumulation was used to evacuate compromised vial through a visual inspection process which could result in deletion of a single observation in a series, or the removal of the entire series. Samples passing visual inspection were analyzed with the HMR package (v0.3.1, Pedersen 2012) in the R statistical environment ("warm puppy" version, R Core

Team, 2013). Briefly, the method fits trace gas concentration time series with either a nonlinear model (Hutchinson and Mosier 1981) or linear regression, or identifies the series as a null flux. When the 95% confidence interval of a nonlinear flux estimate did not include the corresponding linear flux estimate, the nonlinear estimate was used for that series; in all other cases, linear flux estimates were used. Daily fluxes were aggregated to an annual scale by linearly interpolating between consecutive sampling dates and integrating (Smith & Dobbie, 2001)."

A decision making tree was constructed by the Area 4.3 research group to determine whether a given flux was linear, non-linear, or absent. If a non-linear flux were assumed to be linear, the nitrous oxide emission would be greatly overestimated for that sample. Non-linear fluxes were quantified using the Hutchinson and Mosier (1981) approximation. Absent fluxes were given a value of 'zero'. Once the daily fluxes were determined, the annual nitrous oxide flux was calculated for each system by linear interpolation. The annual nitrous oxides fluxes for 2008 through 2012 were averaged into an average annual N_2O flux value for each system.

Gas Flux and Models

Nitrous oxide emissions were considered non-material outputs in the cropping system models. Values were plugged into the cultivation process of each model and are located in Table 16 of the Appendix for the ARL cropping system models and in Table 10 of the Appendix for the KBS cropping system models.

Although carbon dioxide flux data has been collected by the Area 4.3 research group for the cropping systems at both locations, the short term duration of the study was considered insufficient to make meaningful conclusions on soil carbon changes attributable to the specific cropping systems. Therefore, carbon dioxide flux values were based on 20-year soil carbon research conducted at the Long Term Ecological Research (LTER) experiment located at Kellogg Biological Station (Gelfand, in press). If soil carbon is increasing for a treatment, the treatment is sequestering carbon in the form of carbon dioxide from the atmosphere. This will decrease the global warming potential for the treatment. If soil carbon is decreasing for a treatment, the treatment is emitting carbon in the form of carbon dioxide to the atmosphere. This will increase the global warming potential for the treatment. Carbon dioxide values are considered non-material inputs (sequestration) or non-material outputs (emission) in the cropping system models. Carbon dioxide flux values are plugged into the cultivation process of each model and are located in Table 13 of the Appendix for the ARL cropping system models and in Table 13 of the Appendix for the KBS cropping system models.

GaBi 6.0 Professional + Extension Database

Aggregated process data contained in the *Professional + Extension 2012* database in GaBi 6.0 was used for the material and non-material input extraction and production processes in the cropping system models. Processes derived from US data were used whenever possible in the cropping system models. When US derived processes were absent from the *Professional + Extension 2012* database, processes derived from Canadian data were used instead. If both US and Canadian derived processes were absent from the database, any available European processes were used. Cropping system models differ by location due to differences in agronomic inputs and management practices. The final ARL cropping systems models are depicted in Figures 4, 5, 6, 7, 8, 9, 10, 11, 12, and 13. The final KBS cropping system models are depicted in Figures 14, 15, 16, 17, 18, 19, 20, 21, 22,and 23. Solid blue arrows indicate material inputs. Solid black arrows indicate material energy inputs. Dashed blue arrows indicate non-material inputs. Arrows are scaled to show their relative contribution to the system based on mass in kilograms. Material and non-material outputs are not depicted in the cropping system models.

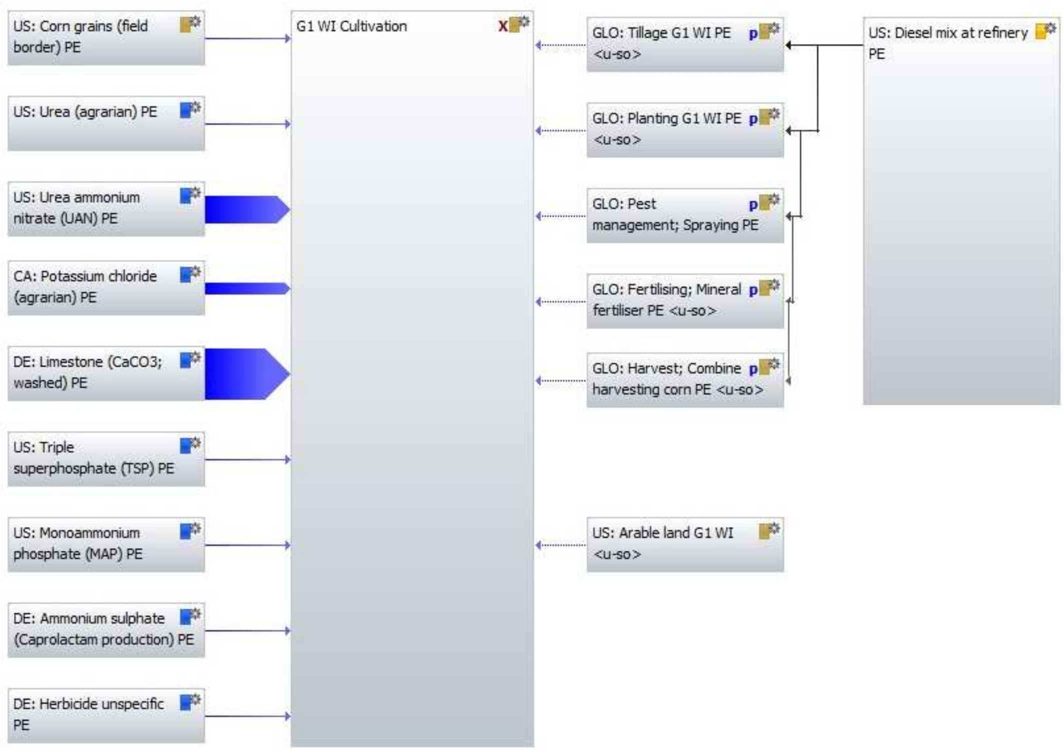


Figure 4. Cropping system model of treatment G1 Continuous at ARL.

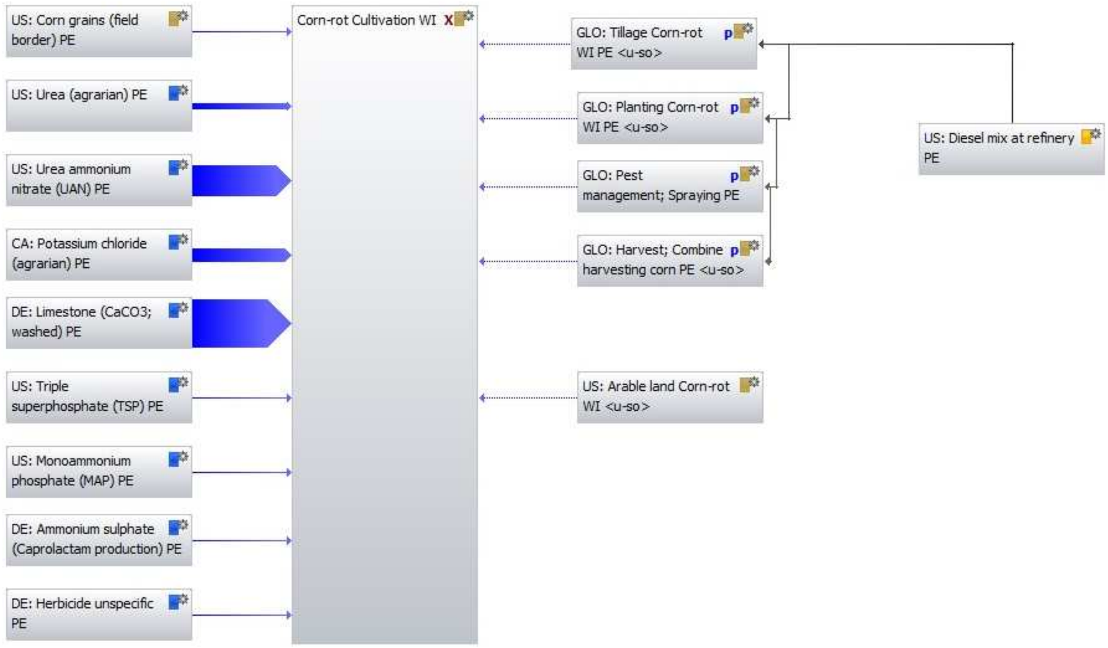


Figure 5. Cropping system model of corn in rotation (corn-rot) at ARL.

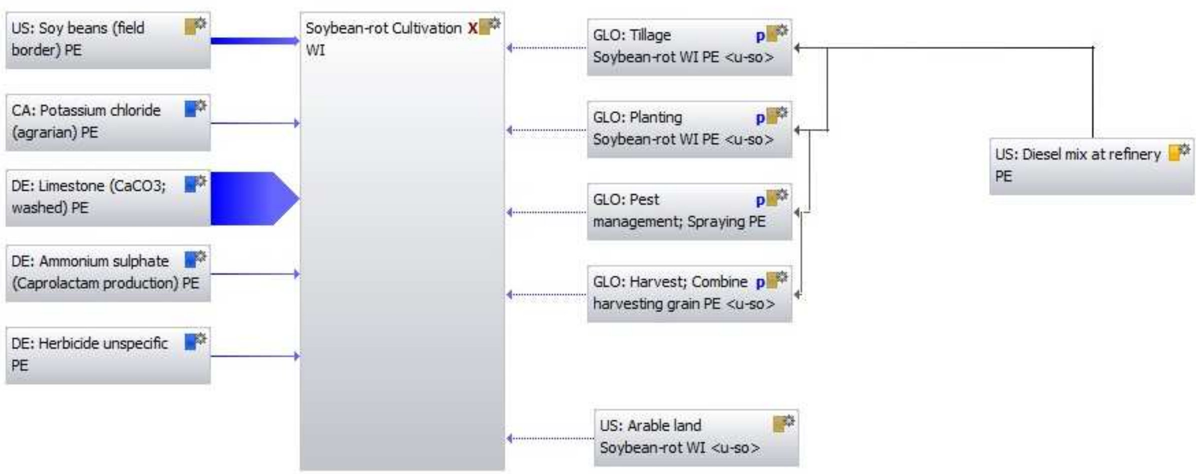


Figure 6. Cropping system model of soybeans in rotation (soybean-rot) at ARL.

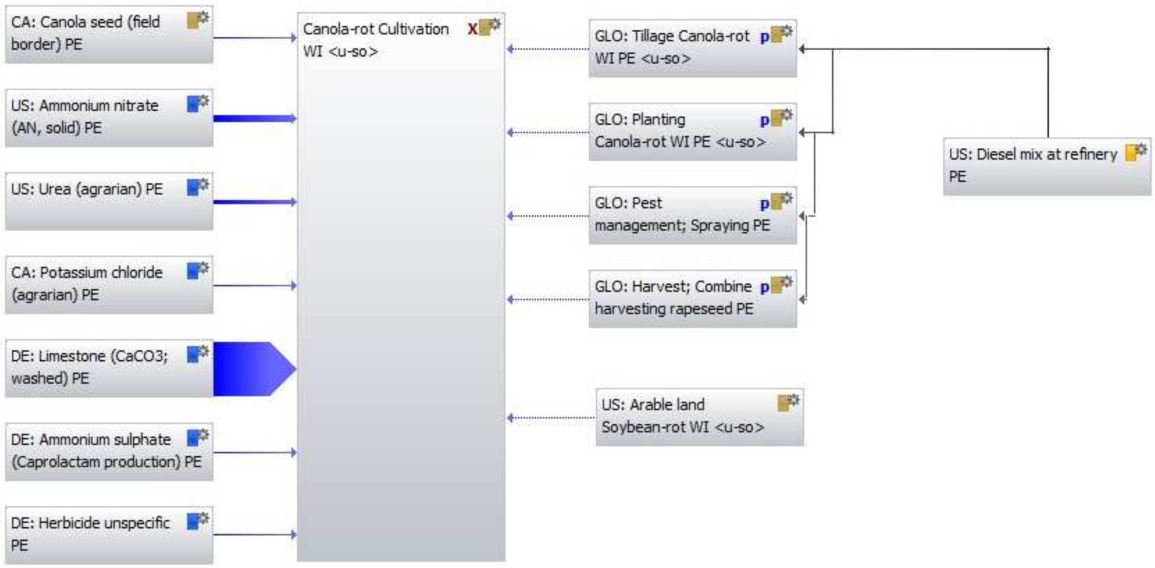


Figure 7. Cropping system model of canola in rotation (canola-rot) at ARL.

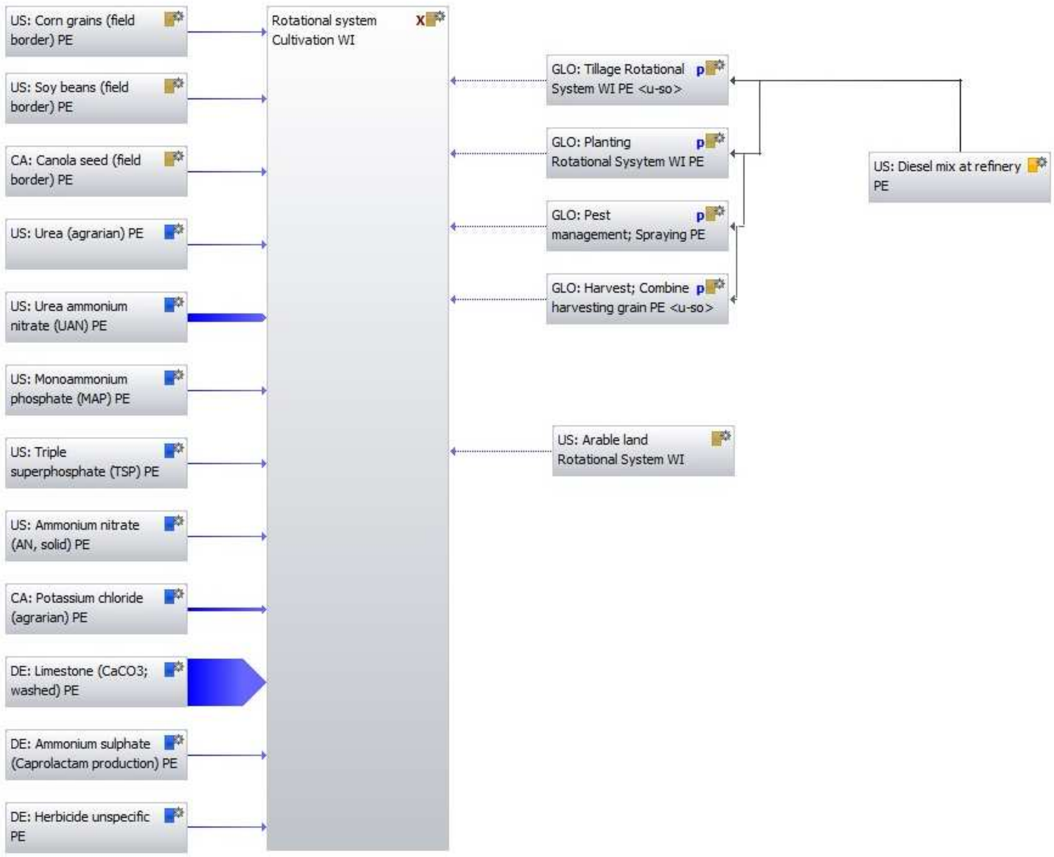


Figure 8. Cropping system model of normalized corn-soybean-canola rotation (rotational system) at ARL.

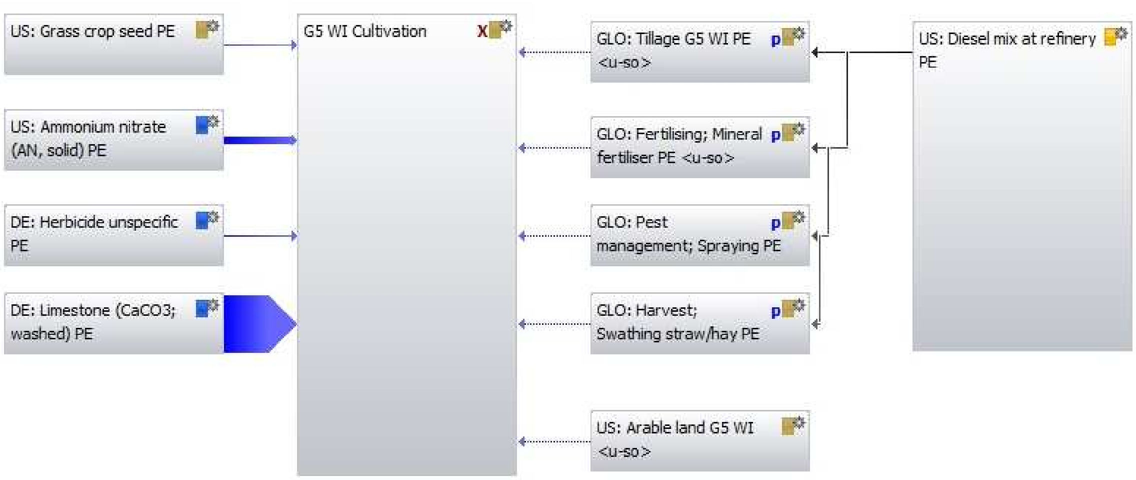


Figure 9. Cropping system model of G5 Switchgrass at ARL.

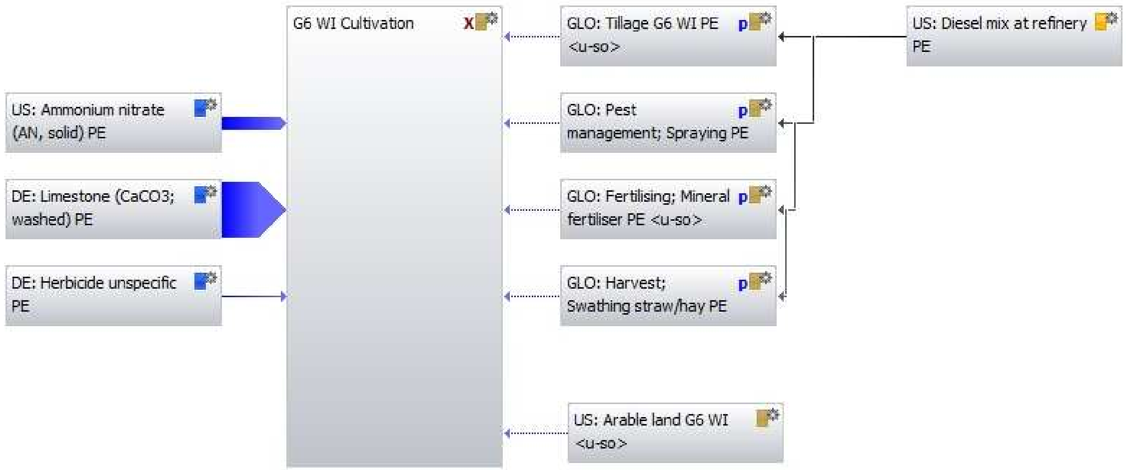


Figure 10. Cropping system model of G6 Miscanthus at ARL.

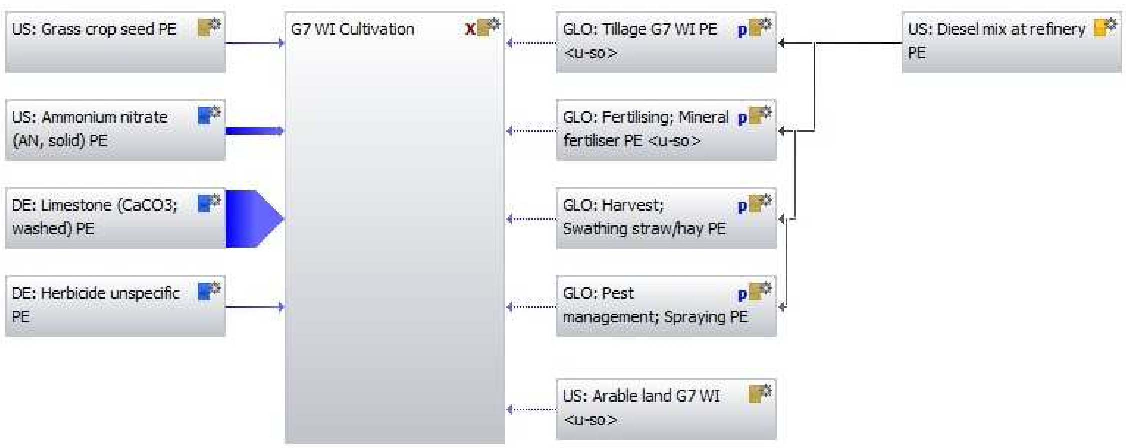


Figure 11. Cropping system model of G7 Native Grass mix at ARL.

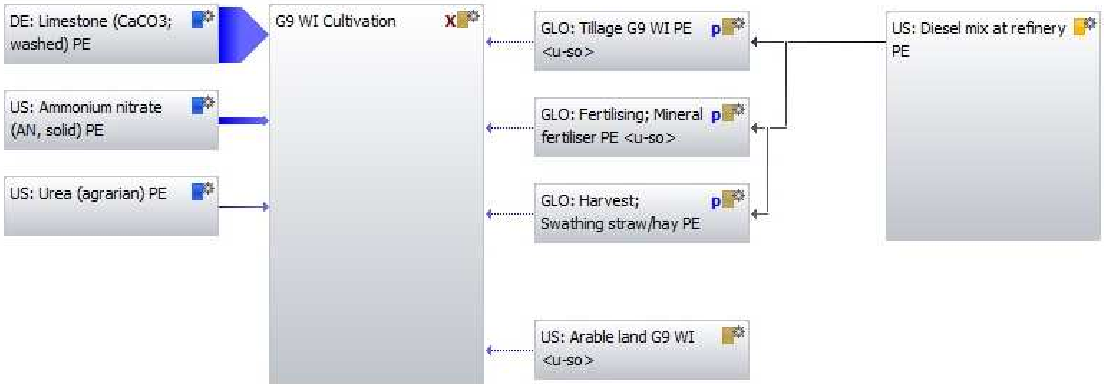


Figure 12. Cropping system model of G9 Old Field at ARL.

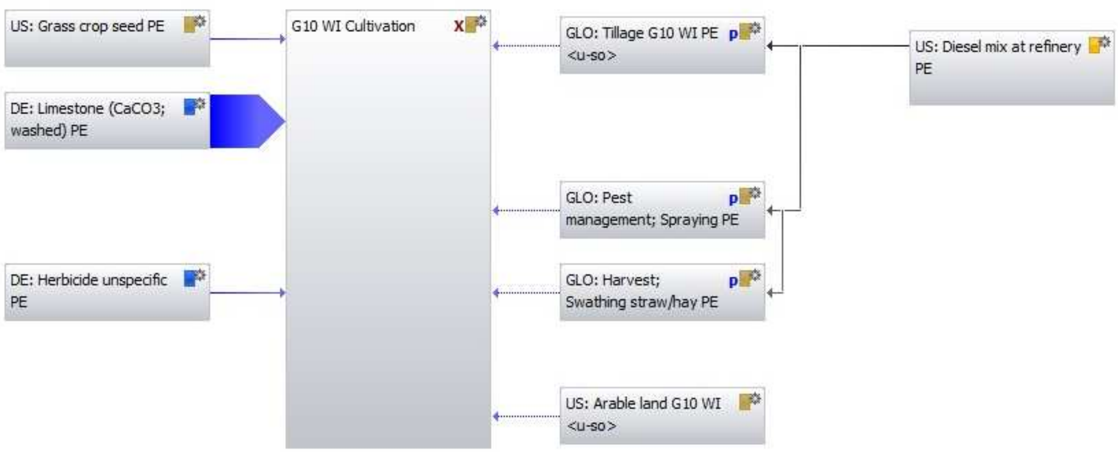


Figure 13. Cropping system model of G10 Native Prairie mix at ARL.

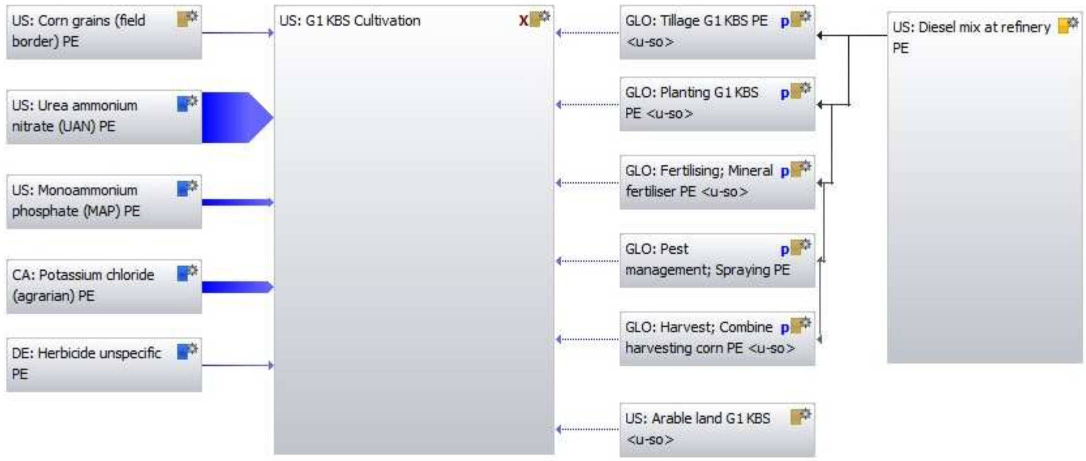


Figure 14. Cropping system model of treatment G1 Continuous at KBS.

Figure 15. Cropping system model of corn in rotation (corn-rot) at KBS.

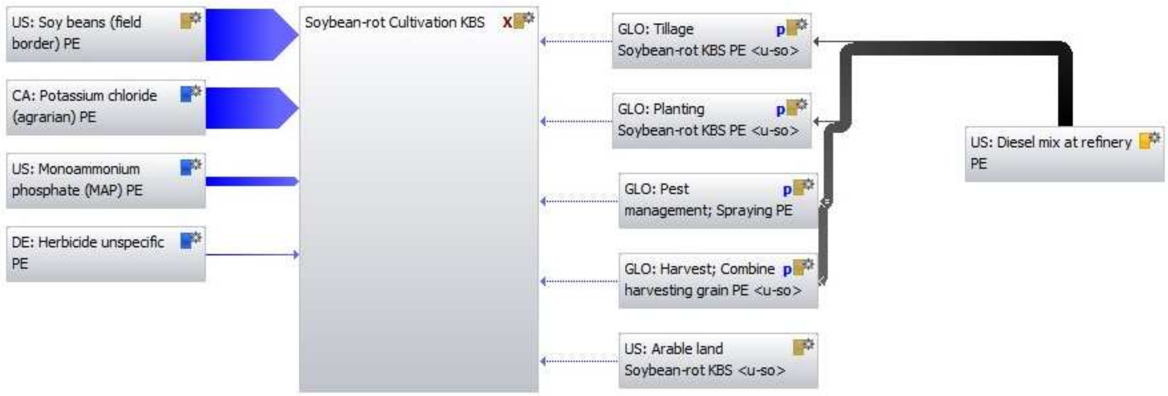


Figure 16. Cropping system model of soybeans in rotation (soybean-rot) at KBS.

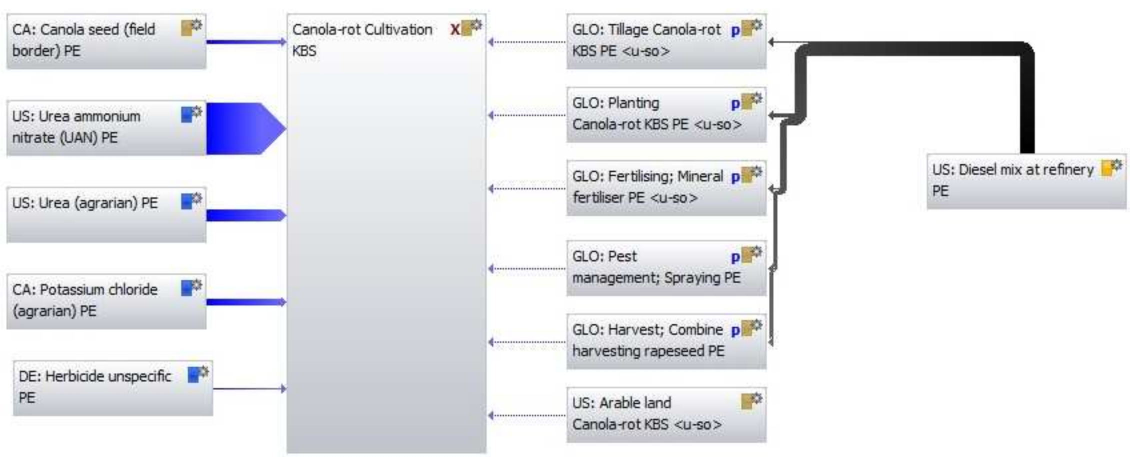


Figure 17. Cropping system model of canola in rotation (canola-rot) at KBS.

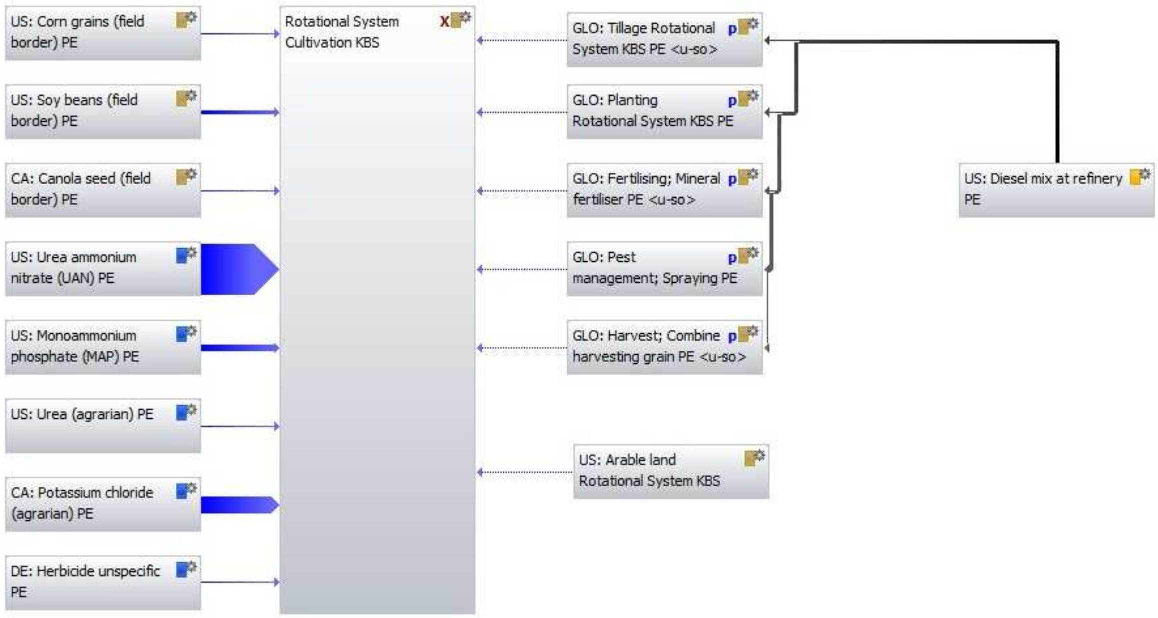


Figure 18. Cropping system model of normalized corn-soybean-canola rotation (rotational system) at KBS.

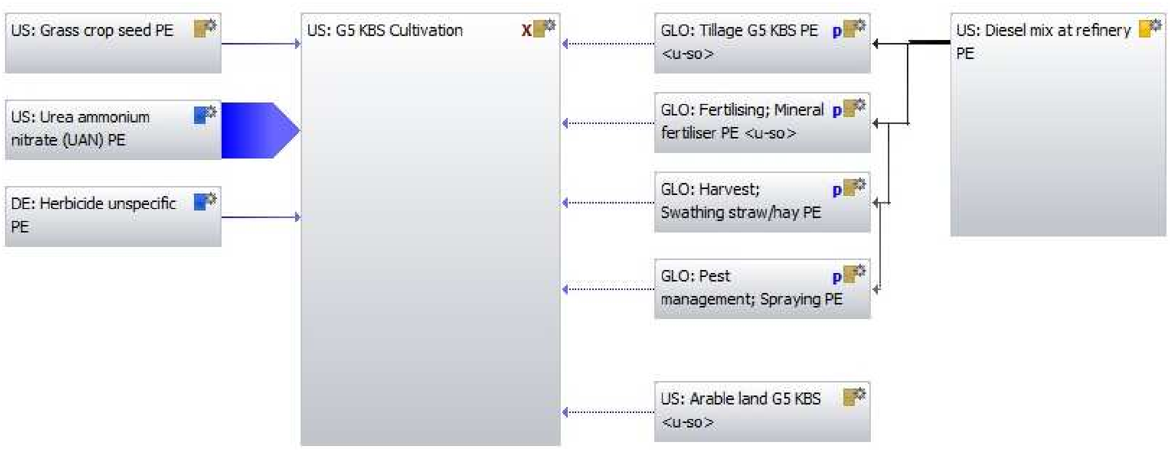


Figure 19. Cropping system model of G5 Switchgrass at KBS.

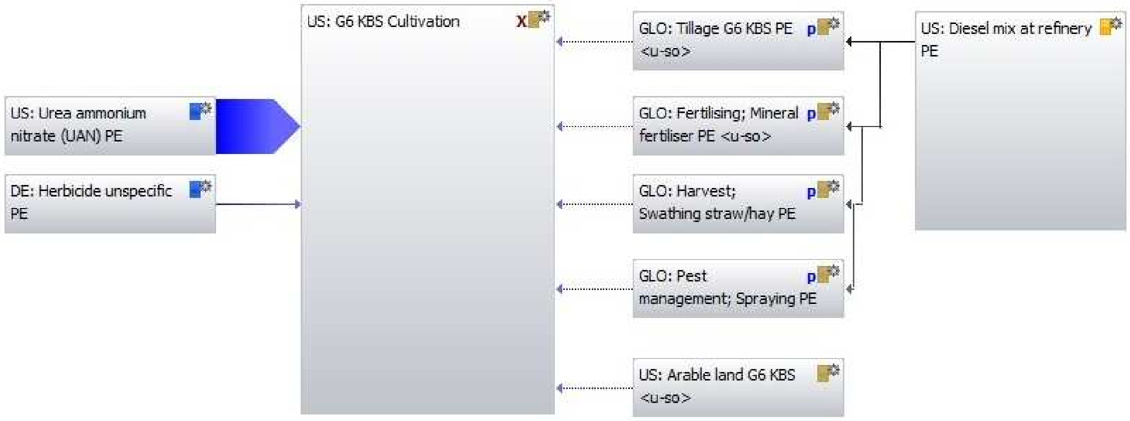


Figure 20. Cropping system model of G6 Miscanthus at KBS.

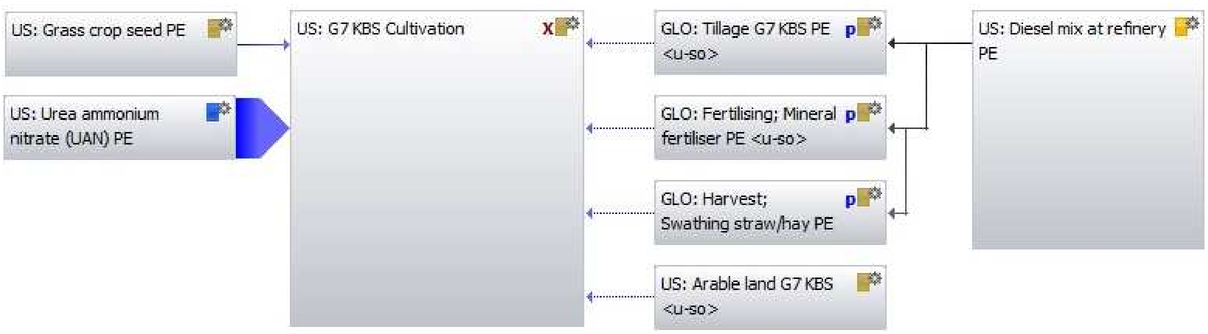


Figure 21. Cropping system model of G7 Native Grass mix at KBS.

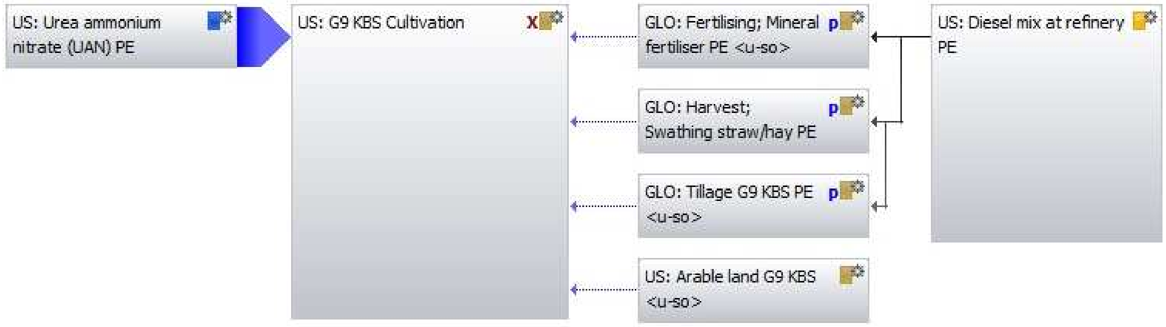


Figure 22. Cropping system model of G9 Old Field at KBS.

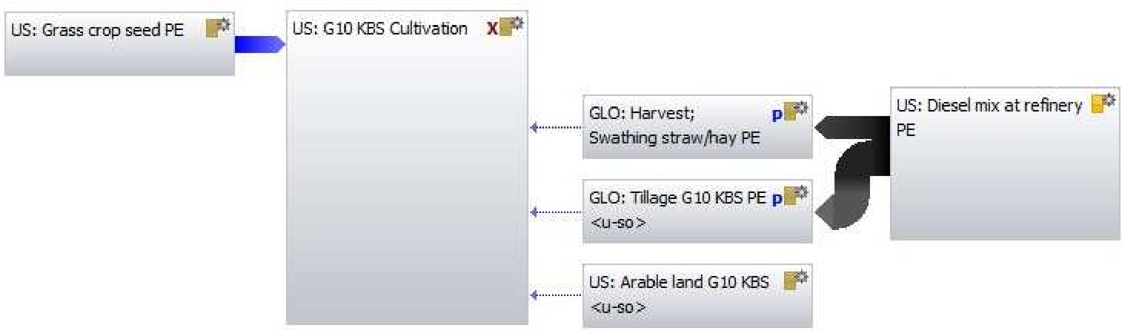


Figure 23. Cropping system model of G10 Native Prairie mix at KBS.

Life-Cycle Impact Assessment (LCIA)

The purpose of the life cycle impact assessment phase is to characterize LCI results into impact categories consistent with the LCA goal. Impact categories can be classified as either midpoint or endpoint. Midpoint categories reflect the magnitude and significance of an environmental emission (calculated in the life cycle inventory) for a system (Bare, 2002).

Midpoint impact categories require simpler models and reduce the uncertainty of the LCIA results due to limiting forecasting and assumptions as compared to endpoint impact categories. Endpoint categories reflect the larger impacts of a life cycle by aggregating multiple impact categories into a single value or score. When aggregating impact categories, specific categories can be weighted based on their perceived relevance to the endpoint. Endpoint impacts can be more comprehensive and leave less room for interpretation than midpoint impacts. The advantages and disadvantages of both types of impact categories should be considered when selecting a life cycle impact assessment methodology.

The goal of this life cycle assessment research was to determine the global warming potential (GWP) of each cropping system, therefore a life cycle impact assessment (LCIA) methodology that included GWP was required for this study. When choosing an LCIA methodology it is also important to consider the geographic parameters included in the methodology framework. Many of the original LCIA methodologies were developed with European parameters and considerations, for example CML 2001 and ReCiPe were both developed in the Netherlands. The geographic scope of this LCA was the north central United States, so methodologies developed for use in Europe likely would not accurately reflect environmental impacts or systems in the US. The LCIA methodology used in this study was TRACI 2.0 because it includes GWP and was developed for use in the US.

TRACI Impact Assessment Methodology

The Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) impact assessment methodology was developed by the US Environmental Protection Agency (EPA) in 2002 with US parameters and characterization factors (Bare, 2002).

An updated and expanded version, TRACI 2.0, was released in 2011. TRACI 2.0 methodology is built into the LCA software, GaBi 6.0, used in this study.

TRACI 2.0 includes midpoint impact categories for ozone depletion, global warming, acidification, eutrophication, smog formation, human health (particulate, cancer, non-cancer), ecotoxicity, and fossil fuel use (Bare, 2002). Figure 24 shows the impact categories included in TRACI 2.0 and their possible endpoints.

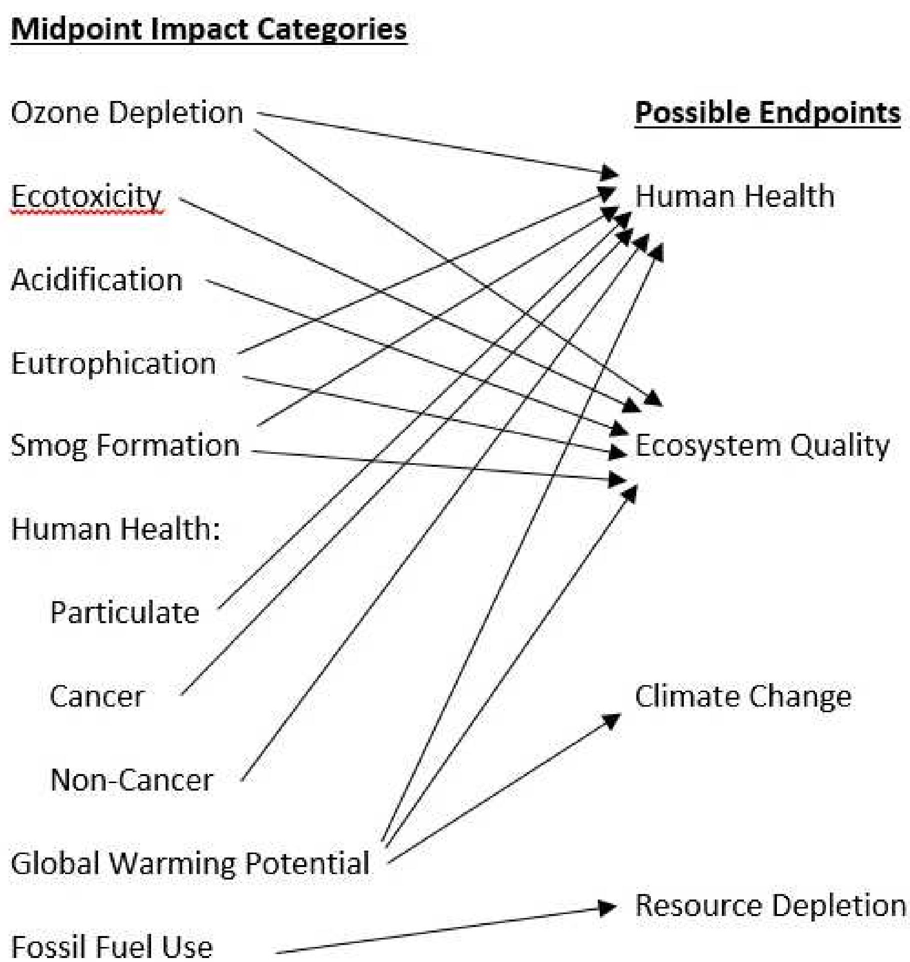


Figure 24. An overview of TRACI 2.0 midpoint impact categories and possible endpoints.

Global Warming Potential Impact Characterization

Greenhouse gases (GHG) that contribute to global warming potential (GWP), as determined by Intergovernmental Panel on Climate Change (IPCC), are included in the TRACI 2.0 midpoint category for GWP. Each gas has its own characterization factor based on a chemical's radiative efficiency and lifetime (IPCC, 2007) as compared to carbon dioxide (the established measurement system). Characterization factors for GWP are determined for a given time horizon, either 20-year, 100-year, or 500-year (IPCC, 2007). This study will use the 100-year time horizon. The mass of an emission is multiplied by the characterization factor resulting in the global warming potential for that emission. The global warming potential for every emission of the life cycle is summed to get the total global warming potential (Bare, 2002).

$$\text{Global Warming Potential of the life cycle} = \sum_i e_i \times GWP_i$$

e_i=emission in kg

$GWP_i =$ global warming potential of substance i=characterization factor of substance i

The GHG emissions from each system were calculated in the life cycle inventory phase. The pathway between the life cycle inventory phase and the life cycle impact assessment phase for GWP is shown in Figure 25.

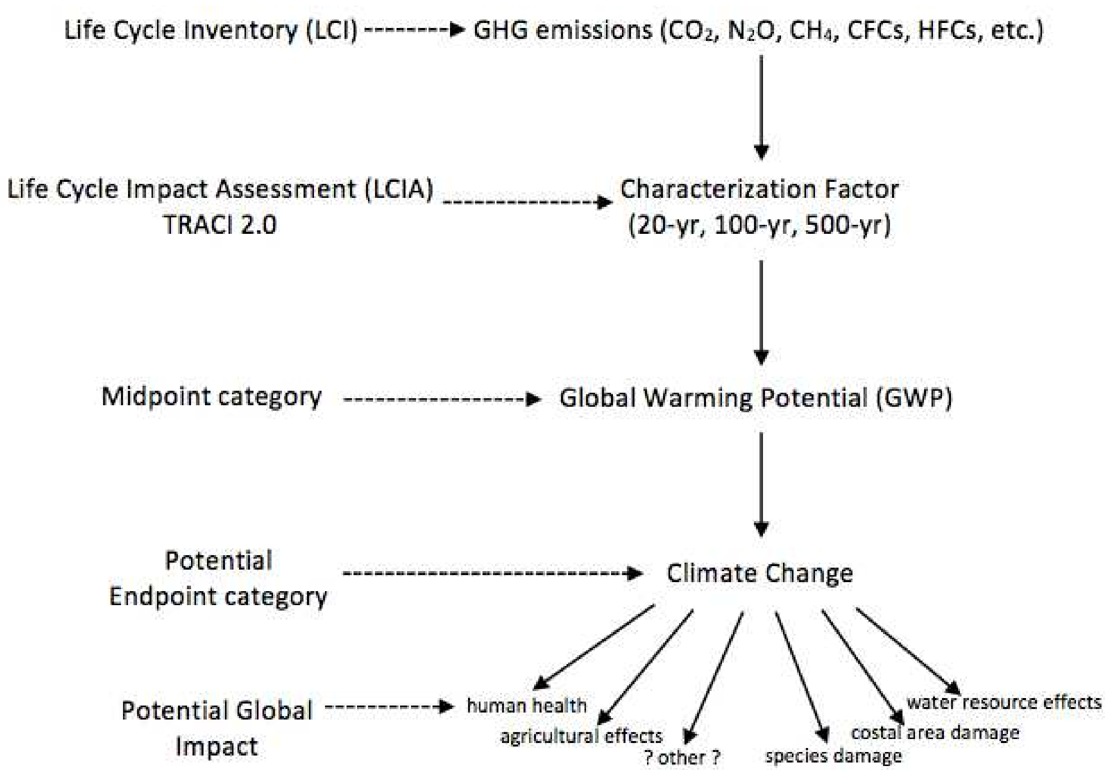


Figure 25. Global warming potential pathway starting at the life cycle inventory phase.

RESULTS

Life Cycle Interpretation

Global Warming Potential

Nitrous Oxide Emissions and Global Warming Potential

The nitrous oxide emissions of a cropping system had a large impact on the global warming potential (GWP) of that system. The average annual nitrous oxide emissions are shown in Figure 26. Error bars represent one standard deviation of the treatment mean for the annual nitrous oxide emissions of each system.

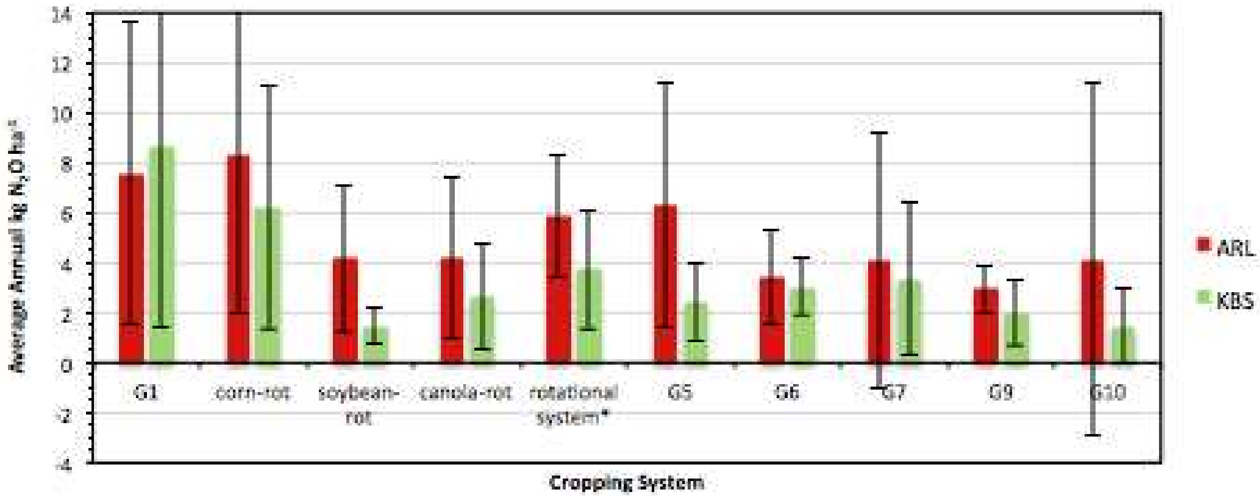


Figure 26. Average annual nitrous oxide emissions of each cropping system for the study years 2008-2012. The * indicates the rotational system values were composed of corn-rot, soybean-rot, and canola-rot data and not directly measured. Error bars represent one standard deviation of the treatment mean between the annual nitrous oxide measurements for each system.

An independent-samples Student's t-test was conducted to compare the nitrous oxide emissions at ARL and KBS for each system. Welch's t-test was used for the soybean-rot and G10 t-tests to account for unequal variances between locations identified from the F-test (data not shown). All other cropping systems were assumed to have equal variances between locations based on the results of the F-test (data not shown). The research hypothesis was that the nitrous oxide emissions for a system would differ by location; the null hypothesis was that the nitrous oxide emissions for a system would be the same at both locations.

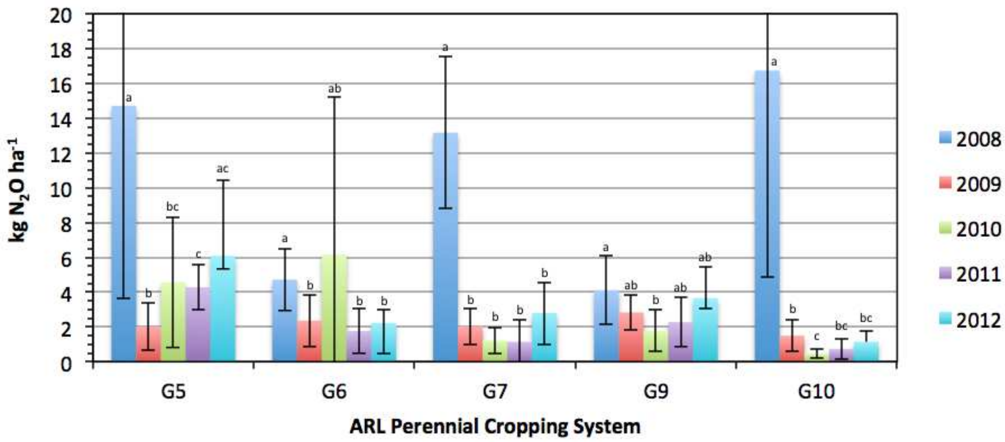
Table 4. Results of the Student's t-test for testing the difference in nitrous oxide emissions between locations for each cropping system (α=0.10).

System	ARL mean	KBS mean	p-value
G1 Continuous Corn	7.58	8.62	0.8225
Corn-rot	8.35	6.21	0.5996
Soybean-rot	4.15	1.46	0.1078
Canola-rot	4.20	2.64	0.4370
Rotational System	5.84	3.74	0.2326
G5 Switchgrass	6.32	2.41	0.1731
G6 Miscanthus	3.44	3.03	0.7159
G7 Native Grass Mix	4.06	3.34	0.8127
G9 Old Field	2.93	2.00	0.2551
G10 Prairie Grass Mix	4.11	1.44	0.4524

The results of the two-tailed t-test failed to reject the null hypothesis for all systems (Table 4.) at the 90% confidence level (α=0.10). Therefore, the nitrous oxide emissions for a system did not differ significantly by location.

Analysis of variance, ANOVA, was also conducted on the nitrous oxide emissions at each location. The ANOVA was used to test whether the means of nitrous oxide emissions were equal for all cropping systems at one location. The research hypothesis was that cropping systems did not emit equal amounts of N_2O; the null hypothesis was that the cropping systems emitted equal amounts of N_2O. At ARL, the results of the ANOVA failed to reject the null hypothesis (p=0.6170, α=0.10). At KBS, the results of the ANOVA rejected the null hypothesis (p=0.0779, α=0.10) meaning that nitrous oxide emissions were not equal across all treatments at this location. Because the results of the ANOVA were not significant at ARL, further post-hoc testing (multiple comparisons) was not performed. Multiple comparison testing was performed for KBS to identify the treatments with significant differences in nitrous oxide emission. At α=0.10, the N_2O emissions from the G1 continuous corn system and the G6 miscanthus system were greater than the N_2O emissions from soybean phase of the rotational system, p=0.0969 and p=0.0573 respectively.

The yearly variation in N_2O emissions for the perennial systems is shown in Figure 27. Perennial systems at ARL had relatively high initial emissions in 2008 compared to the other study years. The perennial systems at KBS did not exhibit the same initial pulse of emissions as ARL; they remained fairly constant across study years.



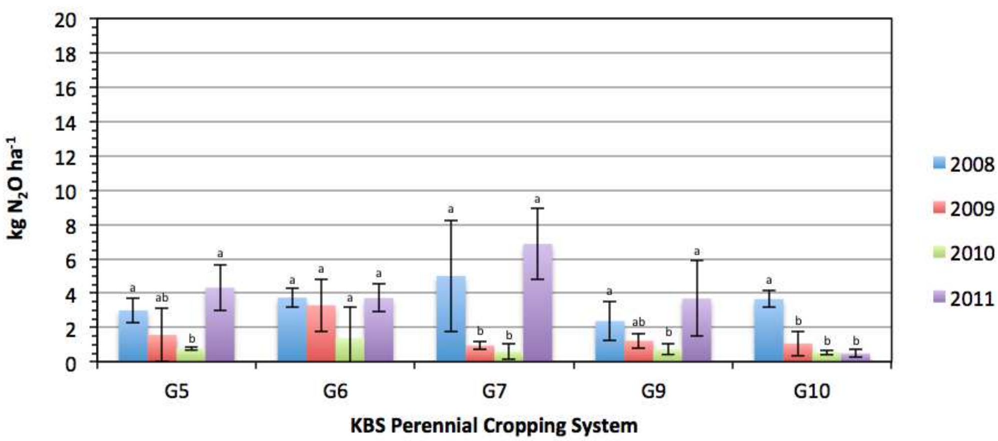


Figure 27. Nitrous oxide emissions by year for the perennial cropping systems at each location. N_2O emission means within each treatment labeled with the same letter are not significantly different from each other (t-test, α=0.10).

The yearly variation in N_2O emissions for the annual systems is shown in Figure 28. Both locations seemed to experience large pulses in nitrous oxide emissions in 2010. Annual systems at ARL in 2012 also saw a moderate pulse in emissions relative to the previous year.

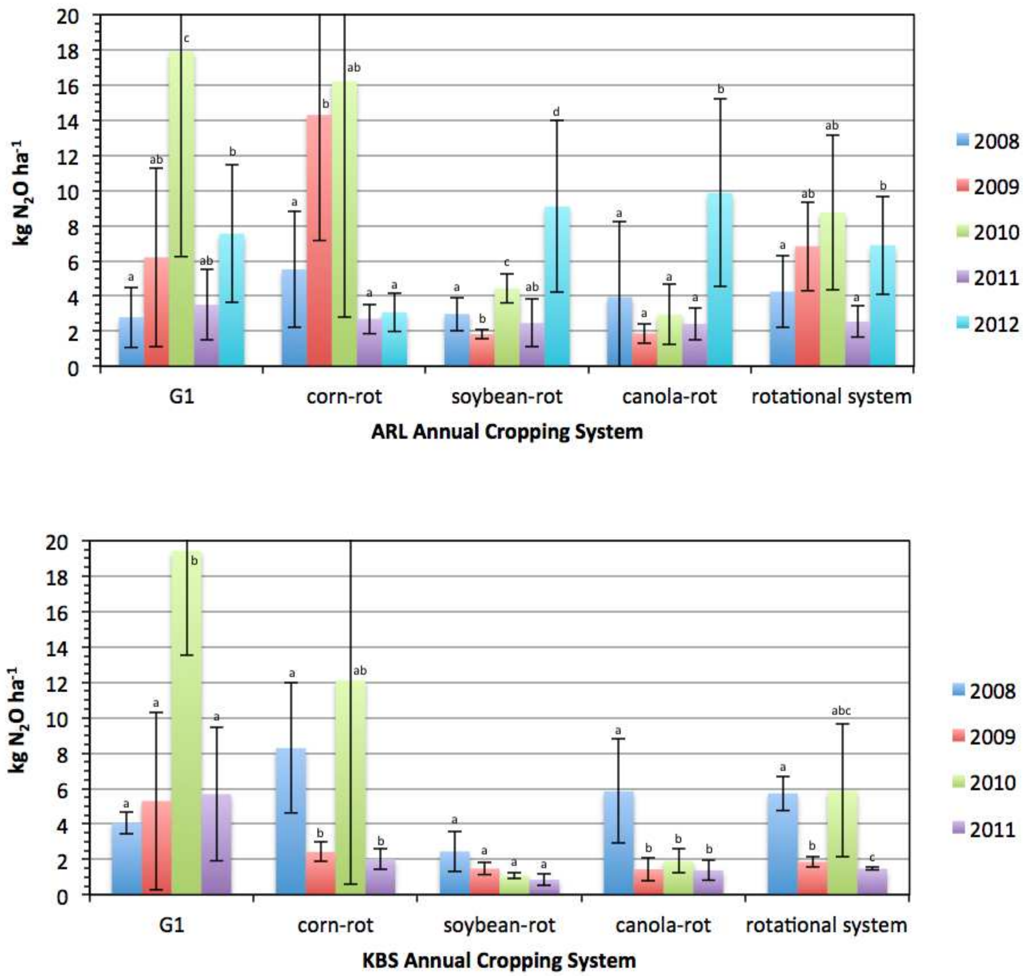


Figure 28. Nitrous oxide emissions by year for the annual cropping systems at each location. N_2O emission means within each treatment labeled with the same letter are not significantly different from each other (t-test, α=0.10). 2012 data was not available for KBS.

Material Inputs and Global Warming Potential

The material inputs that contributed most to the global warming potential of each cropping system were nitrogen fertilizers. Figure 29 and figure 30 show that urea ammonium nitrate (28% UAN) and ammonium nitrate contribute the most to the GWP of each system out of all of the material inputs.

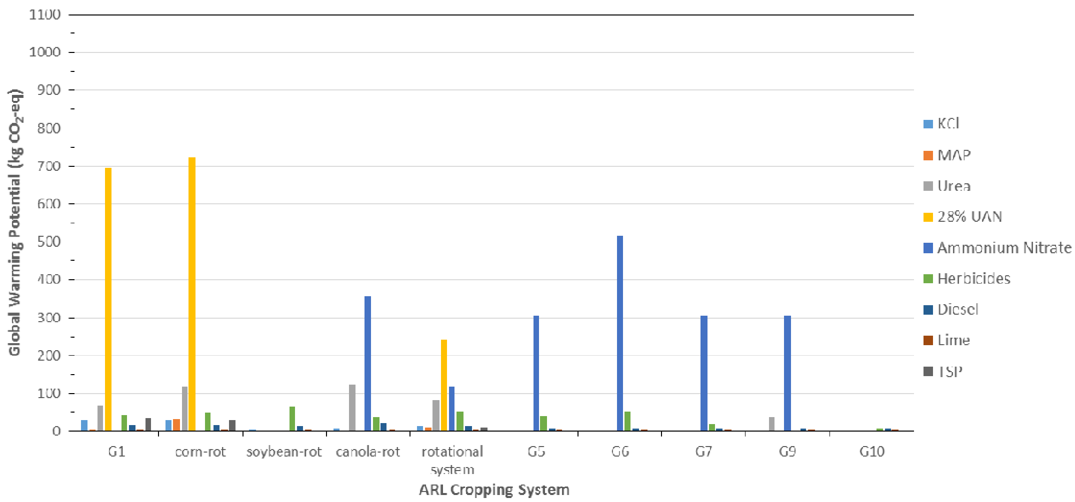


Figure 29. Material input contribution to the global warming potential of each system at Arlington Agricultural Research Station (ARL). Golden yellow bars represent urea ammonium nitrate and royal blue bars represent ammonium nitrate.

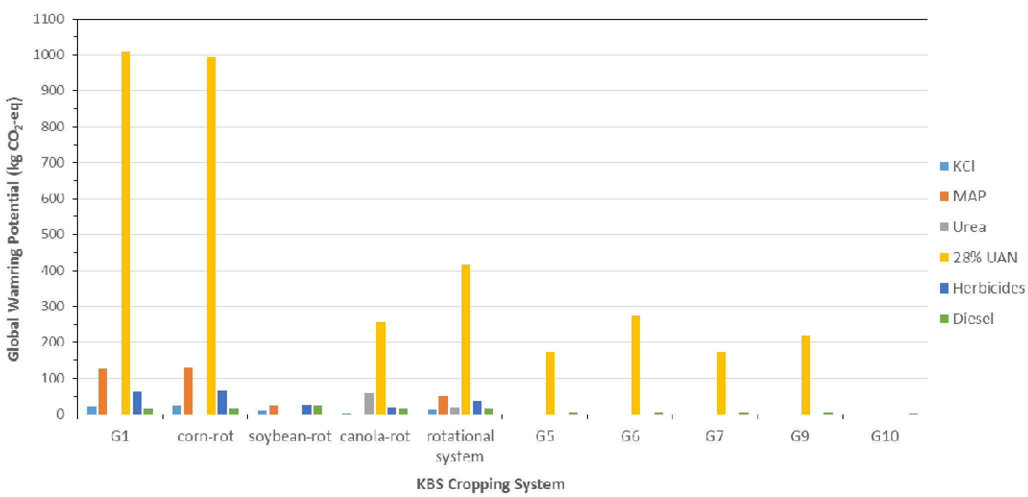


Figure 30. Material input contribution to the global warming potential of each system at Kellogg Biological Station (KBS). Golden yellow bars represent urea ammonium nitrate, grey bars represent urea, and orange bars represent monoammonium phosphate.

ARL used urea ammonium nitrate (UAN) for corn cropping systems and ammonium nitrate for the canola and perennial cropping systems that were fertilized. The differences in nitrogen fertilizer type had an impact on GWP. Ammonium nitrate contributed 9.15 kg CO_2-eq to the GWP per pound of nitrogen (N) applied. Urea ammonium nitrate, a mixture of urea and ammonium nitrate, contributed 6.5 kg CO_2-eq to the GWP per pound of N applied. The use of ammonium nitrate instead of UAN lead to a 28.9% increase in fertilizer contributions to GWP for the perennial and canola systems. Fertilizer production effects were most likely the cause for this difference. Fertilizer production data for ammonium nitrate and UAN is contained in the Professional + Extension 2012 database and was derived from US production sources.

KBS used UAN as the main nitrogen source in all fertilized cropping systems and contributed the majority of GWP from material inputs for each system. Corn systems also have a sizable GWP contribution from monoammonium phosphate (MAP). MAP is commonly used as a starter fertilizer in corn because it supplies both nitrogen and phosphorous, two of the essential nutrients for plants. The canola phase of the rotation system received urea one year instead of UAN. The use of urea instead of UAN lead to a 41.5% decrease in fertilizer contributions to GWP for the year urea was used compared to the years UAN was used in the canola system.

Global Warming Potential on a Land Area Basis

Figure 31 shows the global warming potentials (GWP) for each cropping system in the GLBRC Biofuels Cropping System on a land area basis.

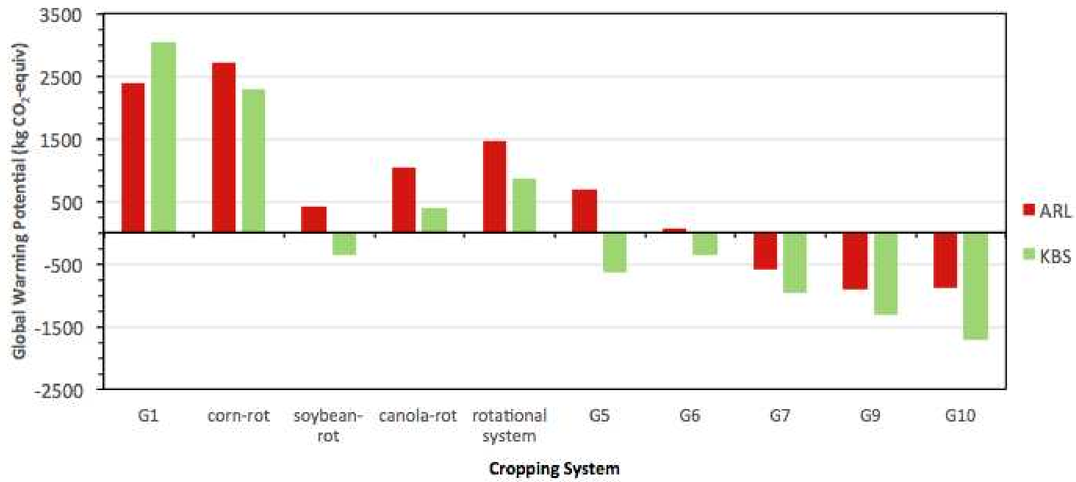


Figure 31. Average global warming potential of each cropping system on a land area basis per year for the study years 2008-2012 (GWP kg CO_2-equiv ha^{-1} yr^{-1}).

Recall, the functional unit for the LCA was one hectare of arable land per year. Except for treatment G1 - continuous corn, ARL cropping systems had a higher GWP than KBS cropping systems. A negative global warming potential indicates a cropping system that is sequestering more GHG from the atmosphere than it is emitting.

Yield

Although GWP is greatest for the corn cropping systems, these systems have the highest potential biofuel yields under current technologies. The grain yield of annual systems and the dry biomass yield of perennial systems were recorded for each location annually (Figure 32).

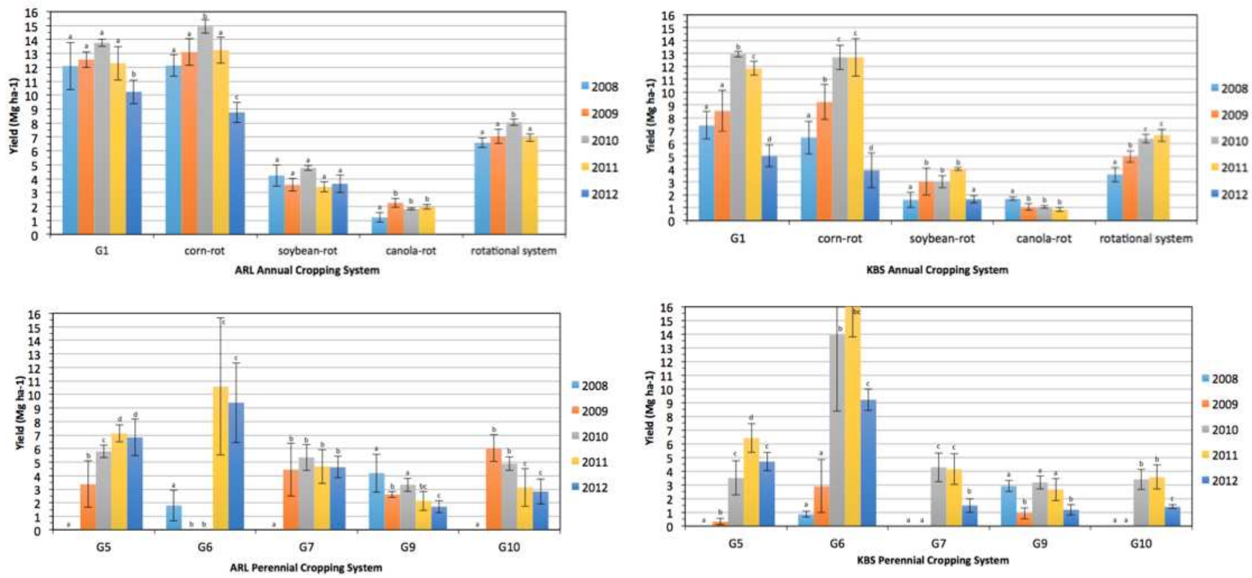


Figure 32. Annual grain yield of annual systems and dry biomass yield of perennial systems. Means within each treatment labeled with the same letter are not significantly different from each other (t-test, α=0.05). Yield unit is Mg ha^{-1}.

Starch-based ethanol conversion was assumed for corn grain systems, biodiesel conversion for soybean and canola systems, and cellulosic ethanol conversion for perennial systems. Average energy (MJ) produced by each system on one hectare of cropping system is shown in Figure 33.

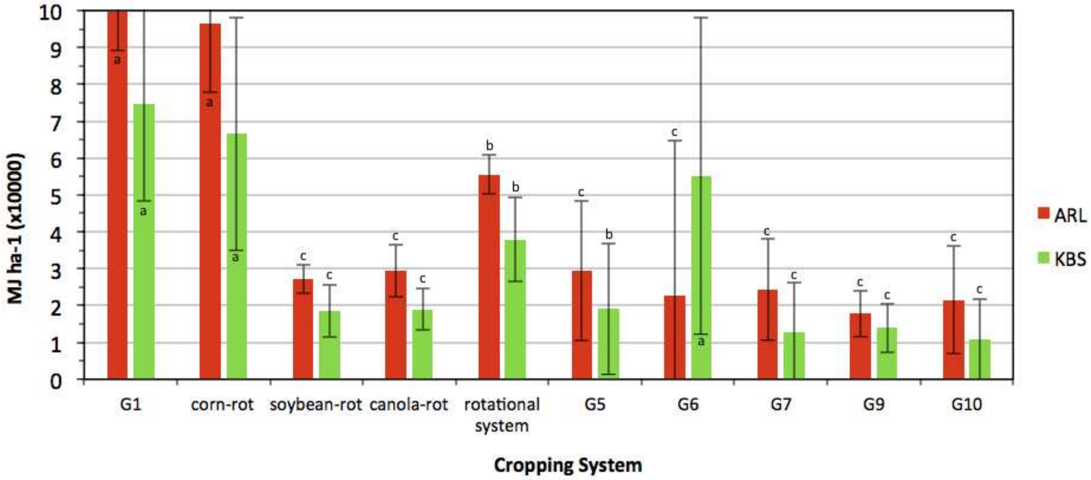


Figure 33. Average estimated energy (MJ) produced on one hectare of each cropping system per year for study years 2008-2012. Energy estimates based on grain ethanol for corn systems, biodiesel for soybean and canola systems, and cellulosic ethanol for perennial systems. Cropping system means labeled with the same letter are not significantly different between treatments per location. (t-test, α=0.10).

Conversion estimates from dry biomass to ethanol do not yet exist for the specific plant communities contained in G6, G7, G9, and G10, so switchgrass conversion factors and estimates were assumed for these systems.

The global warming potential of the estimated amount of gasoline displaced by each cropping system was calculated (Figure 34.). Gasoline displacement calculations assumed the energy in one unit of ethanol (E100) was equal to 0.7 units of gasoline (ethanol producing systems) and one unit of biodiesel (B100) was equal to 0.921 units of petroleum-based diesel (biodiesel producing systems). Gasoline and diesel were assigned a GWP of 91 g CO_2-eq per MJ of energy based on the standard EPA estimates in 2005.

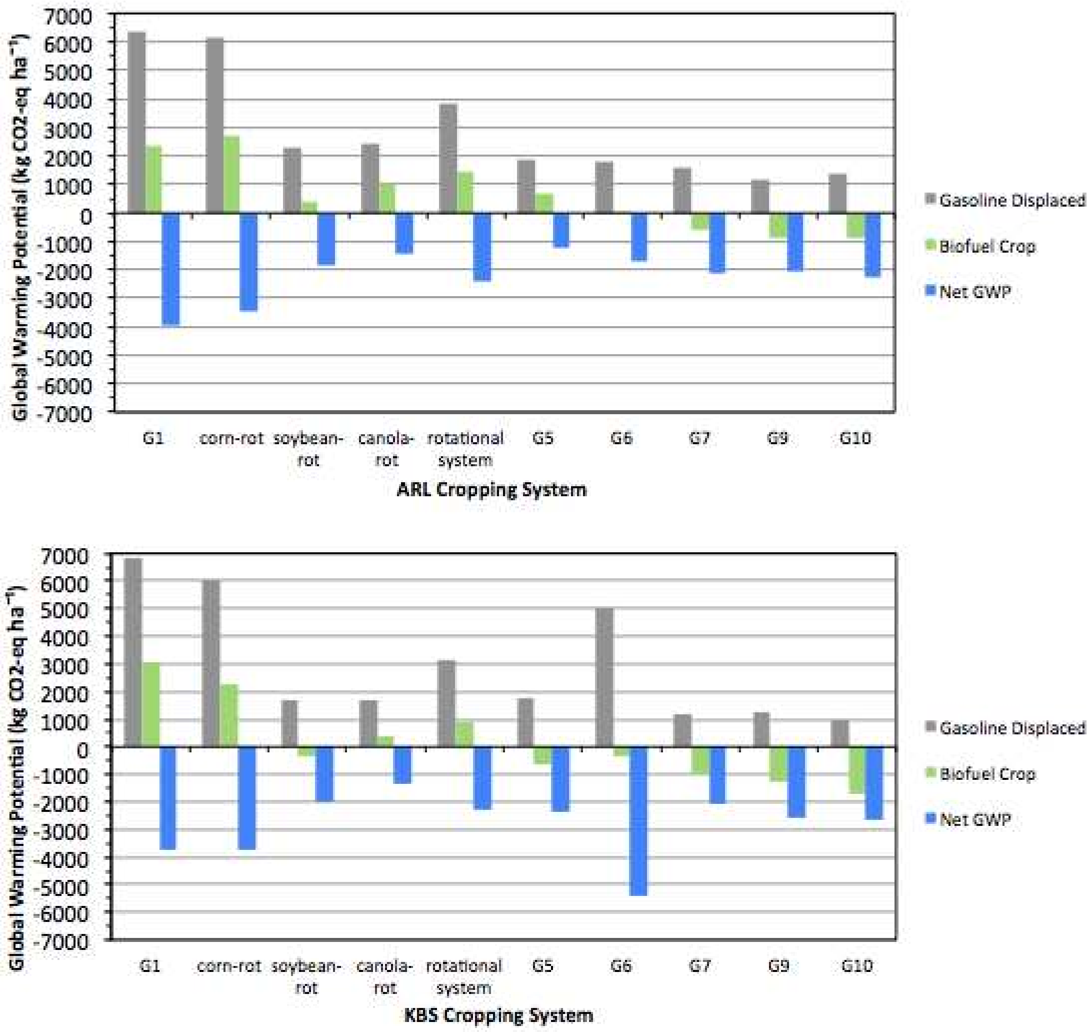


Figure 34. Net global warming potential mitigated (blue bar) by the biofuel crop when compared to equal amounts of fossil fuel energy produced by each system.

An analysis was also performed on the global warming potential per MJ of energy produced in each system. Results are shown in Figure 35. Negative values suggest that the system is sequestering more GHG from the atmosphere than it is emitting during the cropping phase of its life cycle. Theoretically, favorable bioenergy cropping systems should appear in the upper left portion of the graph (high energy output and negative net GWP). The cropping systems containing corn are generally the closest to this location mainly due to high yields, and therefore potential high ethanol production.

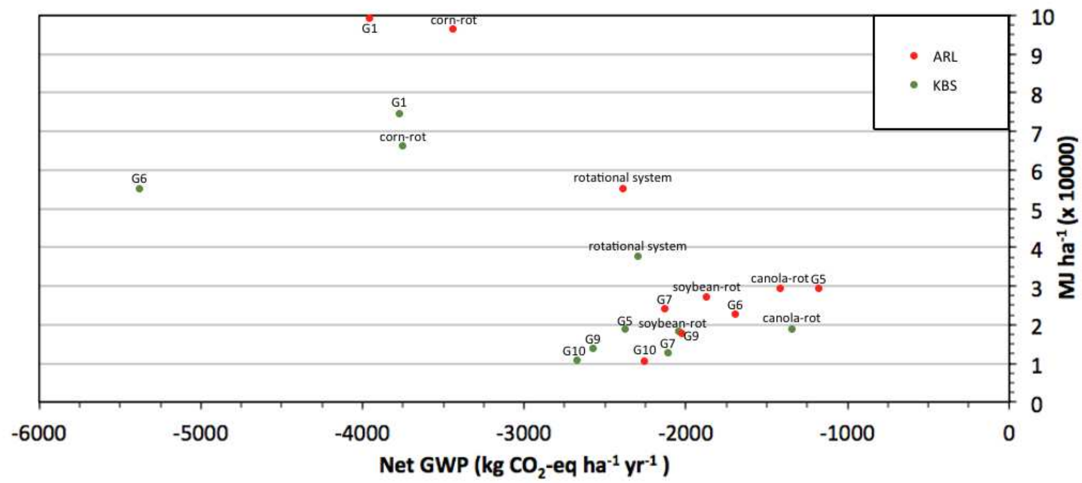


Figure 35. Net global warming potential (kg CO_2-eq ha^{-1} yr^{-1}) verses the energy produced, in MJ, by each cropping system. Cropping systems are labeled above their respective data point.

DISCUSSION

Nitrous Oxide Emissions

Nitrous Oxide emissions had the biggest effect on the global warming potential for a system due to the radiative forcing of N_2O in the atmosphere. Nitrous oxide is produced naturally in agricultural systems through the processes of nitrification and denitrification (Lemke et al., 2008). When weather conditions are warm and moist, soil microbes convert ammonium (NH_4^+) to nitrate (NO_3^-). If nitrate is not taken up by plants it can either be leached from the soil, or denitrified if soil conditions and microbial activity change (Lemke et al., 2008). Denitrification is the microbial process of converting nitrate into N_2O or N_2 gases. The gases are released as emissions from the soil into the atmosphere. N_2 gas does not have a radiative effect in the atmosphere, and therefore is not considered a greenhouse gas. Denitrification occurs in saturated soils (Lemke et al., 2008). Soils can become saturated after periods of heavy rainfall and from snow melt in the spring. Nitrous oxide emissions are generally higher during the spring due to frequent rain events and snowmelt.

The large variations in annual nitrous oxide emissions can explain why no significant differences were identified between locations for each cropping system (Student's t-test) or between cropping systems at each location (ANOVA). The variations in annual N_2O emissions could be due to a number of reasons including local climate conditions and soil type and SOM. ARL experienced slightly cooler temperatures and slightly higher annual precipitation than KBS. The increased precipitation could have increased the soil moisture at ARL and resulted in a greater amount of denitification compared to KBS (Lemke et al., 2008). ARL soils also had a higher SOM content than KBS soils, 3.8% and 2.4% respectively. The decomposition of organic matter could increase the N_2O emissions from high SOM soils (Toma et al., 2011). Although the climate and SOM contents suggest ARL should have higher average annual nitrous oxide emissions, the statistical analysis suggests this is not the case due to high variability in nitrous oxide emissions across both locations.

Fertilizer Sources

The results of the LCA revealed that differences in nitrogen fertilizer source had an impact on the global warming potential. Ammonium nitrate (AN) (34-0-0) contributed about 9.15 kg CO_2-eq per lbs of N applied; UAN (28-0-0) contributed about 6.5 kg CO_2-eq per lbs of N applied; and urea (46-0-0) contributed about 2.69 kg CO_2-eq per lbs of N applied. 28% UAN is a mixture of equal parts urea and AN with enough water to keep the solution in suspension and make up the remainder of the volume. Differences in nitrogen fertilizer source GWP is most likely due to the production phase of the fertilizers. The production phase of a fertilizer includes the extraction of raw materials, the production of energy required throughout the fertilizer production process, and the transportation of fertilizers to their destination (Skowroñska et al., 2014). Fertilizer production mainly contributes to GWP by CO_2 emissions from fossil fuels used in ammonia production and by N_2O emissions during the production of nitric acid. Overall GWP contributions will depend on the type of fertilizer. A recent literature review on fertilizer LCAs by Skowroñska et al., showed similar differences between AN and urea contributions to GWP as this LCA. According to Skowroñska et al., the production phase of AN contributes 6.2 kg CO_2-eq per kg of AN produced; urea contributes 1.59 kg CO_2-eq per kg of urea produced. Although the scales and system boundaries of the Skowroñska et al. are slightly different from those of this study, the same general trends in fertilizer GWP can be seen. Due to lower GWP from the production of urea fertilizers, future fertilizer recommendations could possibly highlight urea as a more 'environmentally friendly' fertilizer choice. It is important to point out that urea fertilizers have the potential to be highly volatile if not incorporated into the soil (by tillage or rainfall) soon after application. Urease inhibitors are also a viable option to decrease the volatilization of urea fertilizers.

Corn Stover

Corn stover was not considered in this LCA because stover removal for ethanol production was not the main plot treatment in the continuous corn system. However, because of future large-scale production potential of cellulosic ethanol from corn stover it should be addressed. Corn stover was harvested in the micro-plot section of each corn treatment every year and yields were recorded. Corn stover was removed at a rate at which the soil organic matter content of the soil would not be greatly affected. Removing too much stover can cause a net loss of carbon from the field resulting in higher erosion, reduced soil tilth, and a net emission of carbon to the atmosphere (likely in the form of CO_2, a GHG). ARL soils have a higher amount of SOM compared to KBS soils, therefore larger amounts of stover were able to be removed at ARL than KBS. The stover harvest at ARL averaged 5.84 Mg ha^{-1} yr^{-1}. Based on a conversion rate of 80 gallons of ethanol per ton (Sheaffer et al., 2010), the stover has the potential to produce 41384 MJ ha^{-1} in addition to the 99522.12 MJ ha^{-1} from corn grain ethanol in the same system. At KBS, the average annual stover harvest was 2.07 Mg ha^{-1} yr^{-1}, capable of producing an additional 14687 MJ ha^{-1} for this system.

Perennial Crops

Miscanthus

Based on yield, miscanthus appears to be a promising perennial crop due to its high biomass yields and therefore high cellulosic ethanol yield potential. The miscanthus cropping system performed well in the life cycle analysis. The global warming potential for miscanthus was slightly positive at ARL (68.7 kg CO_2-eq ha^{-1} yr^{-1}), but negative at KBS (-354 kg CO_2-eq ha^{-1} yr^{-1}). Due to an unadvised first-year biomass harvest, miscanthus winter killed after the 2008 growing season at ARL. The re-establishment of the miscanthus stand at this location may have contributed to a slightly positive GWP. Biomass was not harvested in 2009 or 2010 at ARL to avoid winter kill in the re-established stand. The lack of yield data for these years reduced the dry biomass yield average for ARL miscanthus as seen in Figure 33. If miscanthus had not winter killed at ARL the average yield would be expected to exceed the KBS average yield for 2008-2012.

Old Field Treatment

The biomass yields for treatment G9 - Old Field were fairly consistent across study years for each location. However, the species composition of the harvested biomass changed drastically. At ARL, the plant communities in 2008 and 2009 were dominated by summer annual species: *Echinochloa crus-galli (L.) beauv* (barnyard grass), *Setaria pumila (Poir.) Roem & Schult* (yellow foxtail), *Abutilon theophrasti* (velvetleaf), *Chenopodium album (L.)* (lambsquarters), and *Polygonum pensylvanicum (L.)* (Pennsylvania smartweed). In 2010, the plant communities began to shift to a mixture of summer and winter annuals dominated by: *Conyza Canadensis (L.) cronq.* (marestail) and *Lactuca serriola (L.)* (prickly lettuce). In 2011, the plant community was dominated completely dominated by winter annuals and biennials: *Carduus acanthoides (L.)* (plumeless thistle), prickly lettuce, and *Cirsium vulgare (Savi.) Tenore* (spear thistle). Carson et al. (1988), also identified this successional plant community shift from summer annuals to winter annuals and perennial by the third year of the treatment. Originally, the dominant species were weeds well suited for the disturbed environments of production agricultural systems. Over the study years, increasing competition for resources including light, water, and nutrients resulted in a shift to a competition based dominant species community composition (Lohbeck et al, 2014).

The KBS G9 - Old Field treatment did not start to transition into a winter annual and perennial plant community as described by Carson et al. (1988) until 2012. Species composition was unavailable for 2008. In 2009, 2010, and 2011, the plant community was dominated by summer annual species: lambsquarters, *Digitaria sanguinalis (L.) scop* (large crabgrass), barnyard grass, marestail, and *Setaria viridis (L.) Beauv.* (green foxtail). In 2012, the plant community was dominated by the summer annuals marestail and *Setaria faberi Herrm.* (Japanese bristlegrass), and the winter annual prickly lettuce. It would be interesting see if the 2013 plant community at KBS was completely dominated by winter annuals and perennials or if 2013 was another transition year. The slower transition at KBS could have been due to the marginally productive soils compared to the highly productive soils as ARL. Less productive soils would likely have increased competition for resources within a plant community. With more competition for limited resources, the initial plant species would dominate for a longer period due to the fact that they were already established and reproducing and effectively smothering out other emerging plant species (the winter annuals and perennials).

Land Use Changes

This experiment did not evaluate the potential land use changes for converting prime agricultural land into land for biofuel feedstock production. However, it is worth noting that the perennial cropping systems (G7, G9, G10) with the lowest GWP on a land area basis also produced the least amount of energy per hectare. At ARL, it would take five-times the amount of land under the unfertilized prairie grass mix cropping system to produce the same amount of energy as the continuous corn cropping system per year. At KBS, that factor increases to seven-times the amount of land under the unfertilized prairie grass mix cropping system to produce the same amount of energy as the continuous corn cropping system per year.

As the world's population grows, food production will also have to increase. Converting hectares of prime farmland to biofuel feedstock production isn't reasonable or sustainable for human life. If bioenergy policy continues to push for annual biofuel production requirements, alternative land must be considered. Currently, research is under way on the use of 'marginal lands' for biofuel feedstock production. Marginal land is land that is not fit for crop production due any number of reasons including climate, soil type, water availability, soil fertility, and/or government land management programs. Due to the marginality of this land, successfully establishing perennial crops could be challenging and costly. In addition, fertilizer and soil amendment requirements could be high in order to grow a harvestable quantity of biofuel feedstock. And throughout all of this, economics would be a driving factor in whether or not biofuel crops would be accepted by farmers.

Model Assumption Effects and Considerations

Due to many the assumptions made during this life cycle assessment study, a cautious approach should be taken when interpreting the results. One of the biggest limitations of this study that lead to numerous assumptions was the GaBi LCA software and Professional + Extension 2012 database. GaBi 6.0 is a powerful LCA program. After several classes and tutorials on the software, the practitioner of this study was still only able to perform basic to intermediate level operations and analysis with the software. In addition, the amount of agricultural inputs and processes included in the Professional + Extension 2012 database included in the software was severely limited. Given the nature of the GLBRC Biofuels Cropping Experiment, many of the cropping systems are novel (the perennial systems) and therefore lack the substantial amounts of peer-reviewed literature that is required for inclusion in standard databases.

Miscanthus Rhizomes

There was not a process in the Professional + Extension 2012 database for Miscanthus rhizomes. In fact, there were not any agricultural processes that even remotely resembled or that could be used to represent a miscanthus rhizome. Due to the lack of adequate alternatives, rhizomes as a material input for the miscanthus cropping system were not included in this study. A relatively huge number of rhizomes were used in the field experiment (17,000+ rhizomes ha^{-1}), therefore it can be assumed that the inclusion of rhizomes would impact the results of the miscanthus cropping system in this study. Because all of the other crop seed processes in this study contributed negative values to global warming potential (decreased GWP), the inclusion of miscanthus rhizomes could potentially have the same effect on the miscanthus cropping system GWP.

The current GWP values for this miscanthus cropping systems at ARL and KBS are 68.7 and -354 kg CO_2-equiv ha^{-1} yr^{-1} respectively. If these GWP values were adjusted based on the seed input values for the other cropping systems in the experiment the following new values could be considered for miscanthus:

At ARL, the seed input for the cropping systems accounted for about 1.36% of the total cropping system GWP with the exception of the soybean system at 38.59%. Based on the other cropping system seed input values, if miscanthus rhizomes reduced the currently modeled system's total GWP by 1.36% to 38.59%, the resulting GWP range would be 36.42 to 59.31 kg CO_2-equiv ha^{-1} yr^{-1}.

At KBS, the seed input for the cropping systems accounted for about 1.65% of the total cropping system GWP with the exception of the soybean system at 29.85%. Based on these seed input values, if miscanthus rhizomes reduced the currently modeled system's total GWP by 1.65 to 29.85%, the resulting GWP range would be -412.58 to 535.35 kg CO_2-equiv ha^{-1} yr^{-1}.

Crop Residues as a Co-Product

GaBi 6.0 is a LCA program, not an agricultural systems modeling program. It is designed to model static systems with consistent inputs and outputs. Agricultural systems are the complete opposite of a static system. Agricultural systems are dynamic, always changing depending on number of biotic and abiotic factors at any given time. The program's inability to account for soil dynamics, climate influences, and even field residues as co-products limited this LCA study.

CONCLUSION

A life cycle assessment was performed on each cropping system in the GLBRC Biofuels Cropping System Experiment to identify the global warming potential of one hectare of arable land of each system. Corn cropping systems consistently had the highest GWP at both locations. The unfertilized prairie grass system, G10, had the lowest GWP at both locations. The GWP of a cropping system was heavily influenced by the nitrous oxide emissions for that system. A statistical analysis revealed no significant differences between locations for each cropping system (Student's t-test) or between cropping systems at each location (ANOVA) likely due to the large variations in annual nitrous oxide emissions. G6 - miscanthus, a perennial biomass crop, showed the greatest potential in terms of low GWP and high estimated cellulosic ethanol yield, and therefore the best net GWP from the large displacement of fossil fuels. Due to the exclusion of miscanthus rhizomes as a material input, this particular phase of the life cycle assessment should be investigated in greater detail before a large number of resources are contributed to the development of miscanthus as a biofuel feedstock based on the conclusions of this study.

Limitations imposed by the LCA software and database lead to many model assumptions in this study. These limitations and assumptions require a conservative interpretation of study results.

Potential land use changes, not considered in this study, could have a major impact on future bioenergy policy and biofuel requirements. Potential land use changes and the feasibility of growing dedicated bioenergy crops on marginal lands should be a major area of focus for future biofuel research.

APPENDIX

APPENDIX

Climatological Data

Annual Temperature and Precipitation

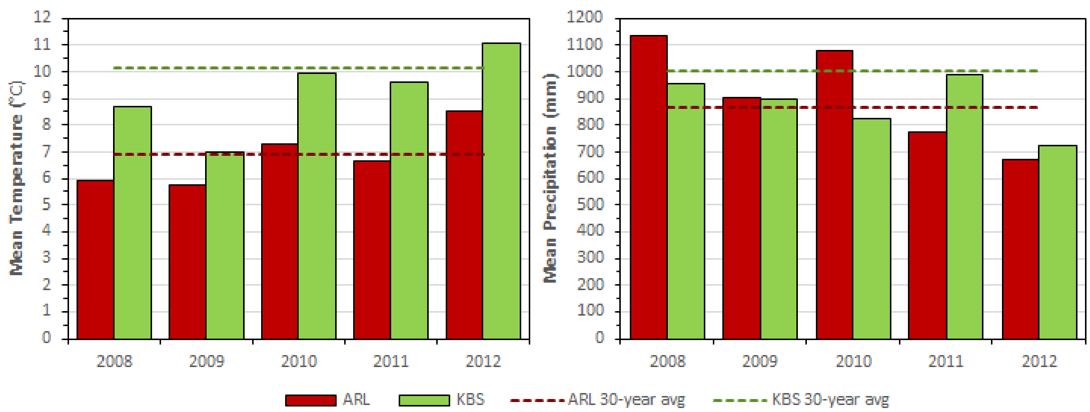
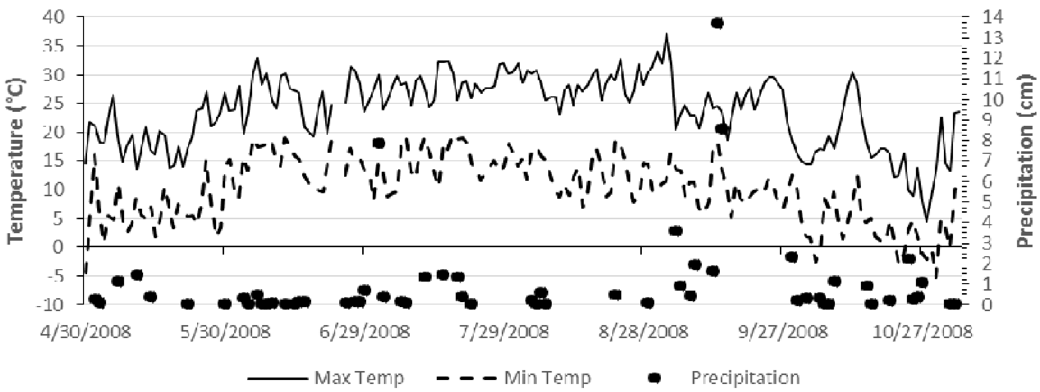


Figure 36. Annual temperature and precipitation for Arlington Agricultural Research Station (ARL) and Kellogg Biological Station (KBS). Annual and 30-year average weather data from National Climatic Data Center (NCDC). 30-year average weather data is from the latest NCDC Climate Normals report for 1981-2010.

Growing Season Temperature and Precipitation

Kellogg Biological Station



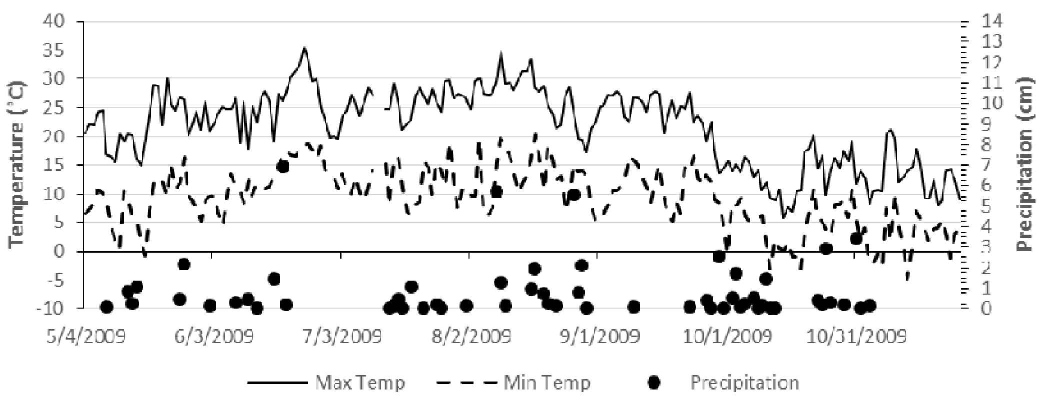
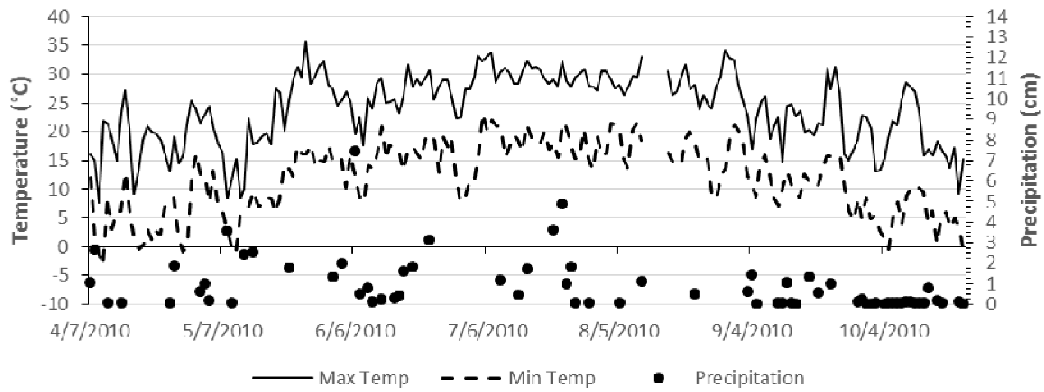
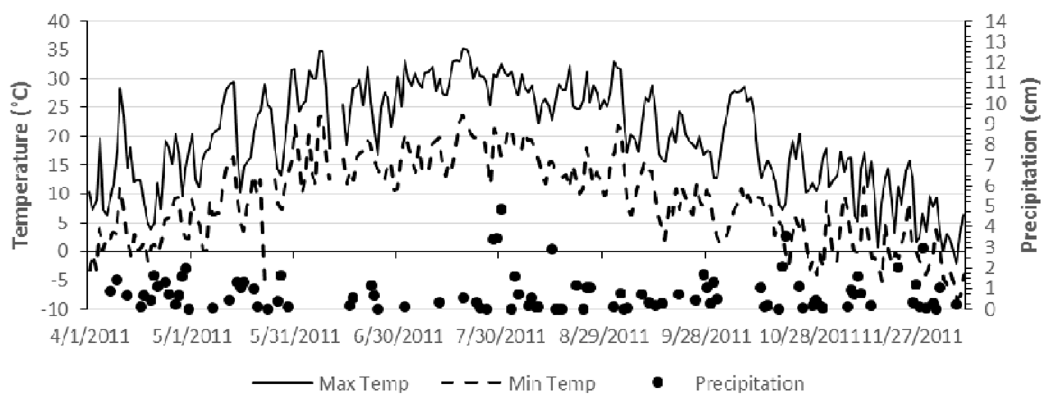
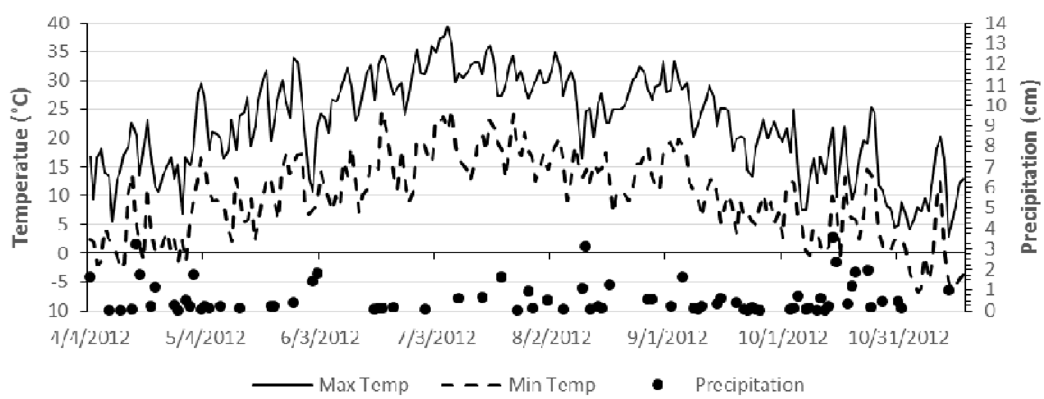


Figure 37. Yearly air temperature and precipitation data from the Hickory Corners weather station recorded by Michigan State University Enviro-weather service. Kellogg Biological Station is located in Hickory Corners, Michigan in close proximity to the weather station. Weather data for 07/15/2009-08/31/2009 was obtained from the Kalamazoo weather station due to no reported data from the Hickory Corners weather station during this timeframe. Kalamazoo is located approximately 18 miles south-east of Hickory Corners.

Figure 37 (cont'd)







Arlington Agricultural Research Station

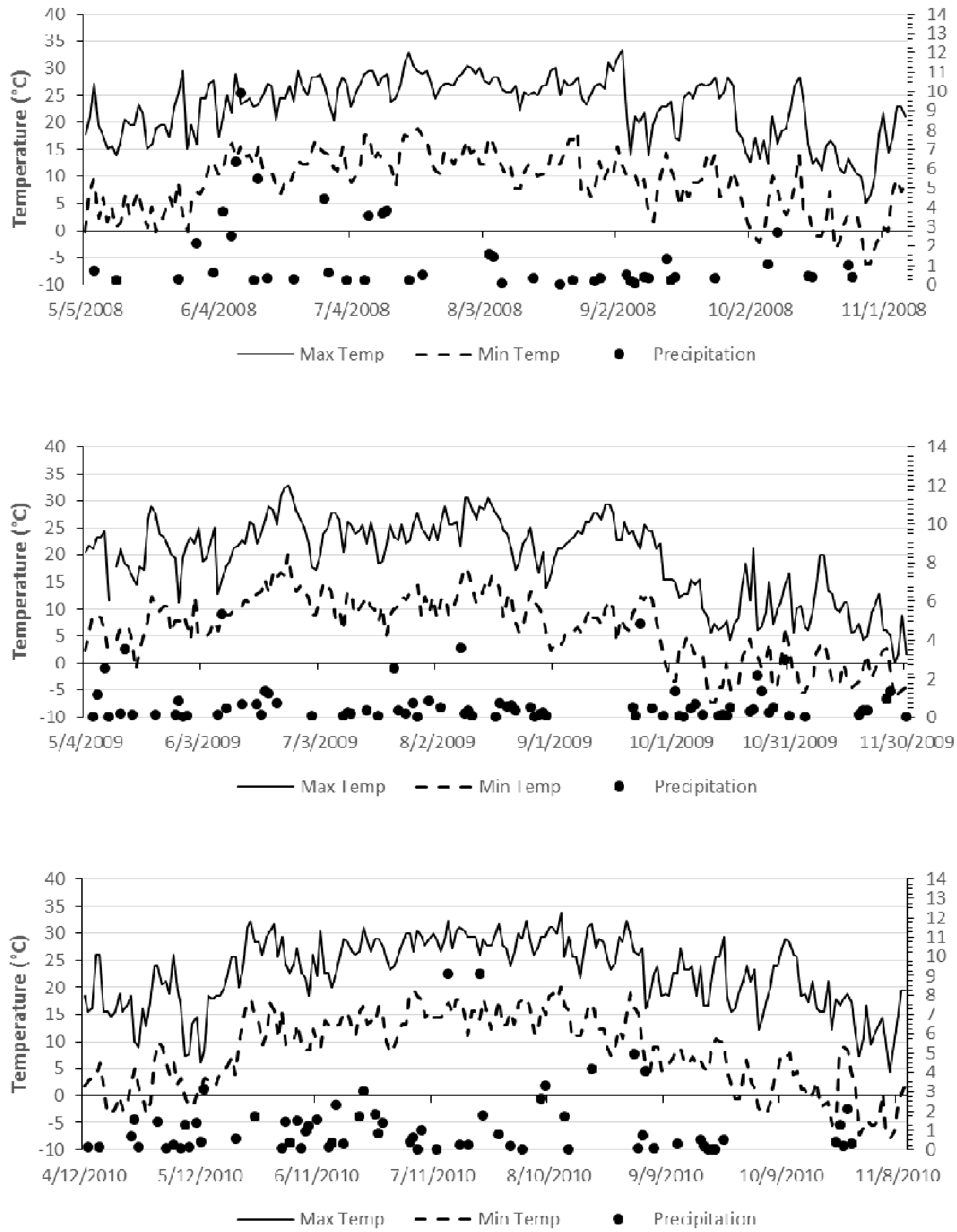
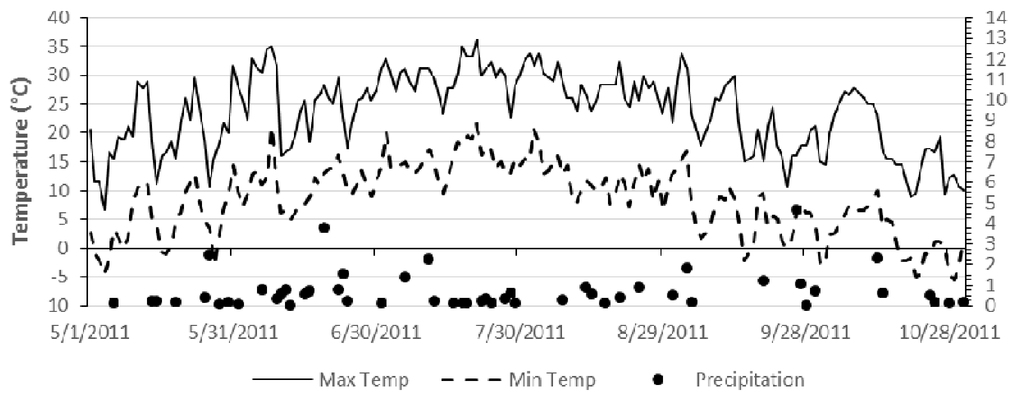
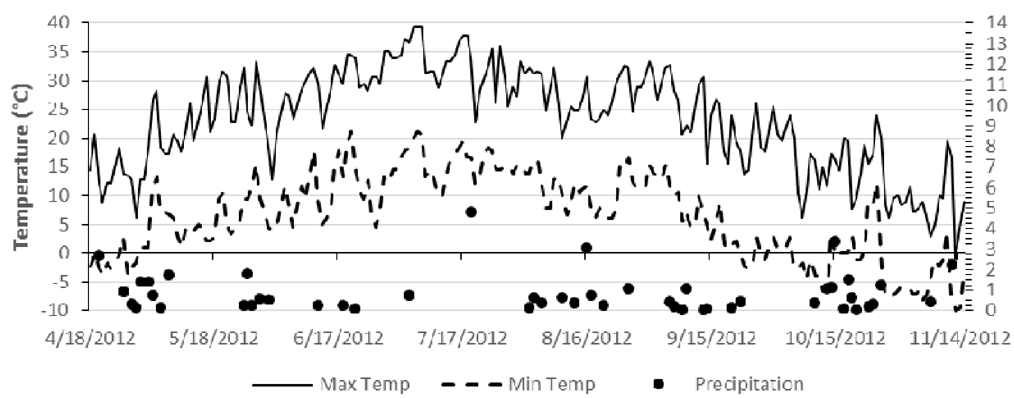


Figure 38. Yearly air temperature and precipitation data from the Arlington University Farm weather station recorded by the National Weather Service.

Figure 38 (cont'd)





Variety and Species Composition

Perennial Crop Mixes

Table 5. Species planted in the perennial cropping systems. Species are the same at both study locations. C_4 and C_3 indicates the photosynthetic pathways of particular grass species.

System	System Name	Group		Species (*latin*)	Common Name / Variety
G5	Switchgrass	Graminoids	C_4	*Panicum virgatum*	switchgrass / Cave-in-rock
G6	Miscanthus	Graminoids	C_4	*Miscanthus x giganteus*	giant miscanthus
G7	Native Grass Mix	Graminoids	C_3	*Elymus canadensis*	Canada wildrye
			C_4	*Panicum virgatum*	switchgrass
				Andropogon gerardii	big bluestem
				Schizachyrium scoparium	little bluestem
				Sorghastrum nutans	Indiangrass
G10	Prairie Grass Mix	Graminoids	C_3	*Koeleria cristata*	prairie Junegrass
				Elymus canadensis	Canada wildrye
			C_4	*Panicum virgatum*	switchgrass
				Andropogon gerardii	big bluestem
				Schizachyrium scoparium	little bluestem
				Sorghastrum nutans	Indiangrass
		Legumes		*Desmodium canadense*	showy ticktrefoil
				Lespedeza capitata	roundhead lespedeza
				Baptisia leucantha	white false indigo
		Early forbs		*Rudbeckia hirta*	blackeyed Susan
				Anemone canadensis	Canadian anemone
				Asclepias tuberose	butterfly milkweed
		Mid forbs		*Silphium perfoliatum*	cup plant
				Monarda fistulosa	wild bergamot
				Ratibida pinnata	pinnate prairie coneflower
		Late forbs		*Solidago rigida*	rigid goldenrod
				Solidago speciosa	showy goldenrod
				Aster novae-angliae	New England aster

Annual Crops

Kellogg Biological Station

Table 6. Annual crop variety by year at KBS.

System	Year	Variety	Notes
G1	2008	Dekalb DKC 52-59 Corn Hybrid	
	2009		
	2010		
	2011		
	2012		
corn-rot	2008	Dekalb DKC 52-59 Corn Hybrid	
	2009		
	2010		
	2011		
	2012	Dekalb DKC 48-12 RIB Corn Hybrid	
soybean-rot	2008	Pioneer 91M80 RR Soybeans	
	2009	Pioneer 92Y30 Soybeans	
	2010		
	2011		
	2012		
canola-rot	2008	winter canola; Dekalb DKL 52-10 RR Spring Canola	no variety information for winter canola; canola was replanted in spring
	2009	Dekalb DKL 52-10 RR Spring Canola	
	2010		
	2011	Dekalb Genuity RR Canola DKL 72-55	

Arlington Agricultural Research Station

Table 7. Annual crop variety by year at ARL.

System	Year	Variety	Notes
G1	2008	Dekalb 52-59 RR	
	2009	Pioneer 35F40 RR/LL/Bt	
	2010	Delkalb 52-59 RR/Bt	
	2011		
	2012	Pioneer 35F40	
corn-rot	2008	Dekalb 52-59 RR	
	2009	Pioneer 35Y40 RR/LL/Bt	
	2010	Dekalb 52-59 RR/Bt	
	2011		
	2012	Great Lakes 4041G3VT3	
soybean-rot	2008	Pioneer 92Y40 RR	
	2009	Dairyland 2200 RR	
	2010	Pioneer 92Y51	
	2011	Dairyland 2375/R2Y	
	2012	Dairyland 2011	
canola-rot	2008	Dekalb 5210 RR	spring canola
	2009	InVigor 8440 LL	
	2010		
	2011		

Herbicide

Arlington Agricultural Research Station

Table 8. Herbicides used at ARL. Chemical and trade names are listed.

Chemical Name	Trade Name(s)	Crops
glyphosate	Honcho Plus; Mirage Plus; Roundup PowerMAX	corn; canola; switchgrass; miscanthus; native grass mix; prairie grass mix
s-metolachlor	Dual II Magnum;	corn; soybean; miscanthus
2,4-D ester		corn; soybean; canola; switchgrass; miscanthus; native grass mix
mesotrione	Callisto	corn
simazine	Princep	corn
tembotrione	Laudis	corn
sulfentrazone; cloransulam-methyl	Authority First	soybean
glufosinate		soybean; canola
dicamba	Clarity	switchgrass
quinclorac		switchgrass
pendimethalin	Prowl	miscanthus

Kellogg Biological Station

Table 9. Herbicides used at KBS. Chemical and trade names are listed.

Chemical Name	Trade Name(s)	Crops
glyphosate	Roundup OriginalMAX; Roundup PowerMAX;	corn; soybean; canola
s-metolachlor; atrazine; mesotrione	Lexar	corn
2,4-D ester		corn; soybean
glufosinate	Ignite	corn
quinclorac	Drive	switchgrass; miscanthus
2,4-D amine		switchgrass

Cropping System Model Data

Kellogg Biological Station

Material Inputs

Table 10. Material inputs at KBS per reference flow of 1 ha year^{-1}.

System	Material Input	Value (kg ha^{-1})	Source	Notes
G1	seed	20.05	KBS field data	
	(28-0-0) urea ammonium nitrate	554.50		
	(10-34-0) ammonium polyphosphate	86.5		
	(0-0-60) potash	131.36		
	herbicide (total)	9.24		Herbicides: Lexar; Roundup OriginalMAX; 2,4-D; Roundup PowerMAX
	diesel	31.03	Stein, 2012	
corn-rot	seed	20.30	KBS field data	Corn phase data from: G2-2008 G2-2011 G2-2012 G3-2010 G3-2012 G4-2009
	(28-0-0) urea ammonium nitrate	544.67		
	(10-34-0) ammonium polyphosphate	88.67		
	(0-0-60) potash	141.83		
	herbicide (total)	9.72		
	diesel	31.11	Stein, 2012	
soybean-rot	seed	81.32	KBS field data	Soybean phase data from: G2-2009 G3-2008 G3-2011 G4-2010 G4-2012
	(0-0-60) potash	64.00		
	(11-52-0) monoammonium phosphate	15.20		
	herbicide (total)	3.63		
	diesel	31.11	Stein, 2012	
canola-rot	seed	11.34	KBS field data	Canola phase data from: G2-2010 G3-2009 G4-2008 G4-2011
	(28-0-0) urea ammonium nitrate	140		
	(46-0-0) urea	36.50		
	(0-0-60) potash	23.75		
	herbicide (total)	2.68		
	diesel	29.55	Stein, 2012	
G5	seed	8.98	KBS field data	
	(28-0-0) urea ammonium nitrate	94.4		
	herbicide (total)	0.56		Herbicides: 2,4-D; Drive
	diesel	35.87	Stein, 2012	
G6	rhizomes	-	KBS field data	see assumptions
	(28-0-0) urea ammonium nitrate	149.6		
	herbicide (total)	0.11		Herbicide: Drive
	diesel	34.78	Stein, 2012	
G7	seed	1.79	KBS field data	
	(28-0-0) urea ammonium nitrate	94.40		
	diesel	35.79	Stein, 2012	
G9	(28-0-0) urea ammonium nitrate	118.8	KBS field data	
	diesel	28.69	Stein, 2012	
G10	seed	1.79	KBS field data	
	diesel	34.93	Stein, 2012	

Non-Material Inputs

Table 11. Non-material inputs at KBS per reference flow of 1 ha year^{-1}.

System	Non-Material Input	Number of trips across plot)	Source	Notes
G1	Tractor	4.2	KBS field data	
	Sprayer	2		
	Planter	1		
	Tillage	0.2		
	Combine	1		
	Fertilizer Applicator	1		
corn-rot	Tractor	4	KBS field data	
	Sprayer	1.5		
	Planter	1		
	Tillage	0.17		
	Combine	1		
	Fertilizer Applicator	1.17		
soybean-rot	Tractor	4.4	KBS field data	
	Sprayer	2.8		
	Planter	1.4		
	Tillage	0.2		
	Combine	1		
canola-rot	Tractor	4	KBS field data	
	Sprayer	2.75		
	Planter	1		
	Tillage	0.25		
	Combine	1		
G5	Tillage	0.8	KBS field data	
	Tractor	2		
	Planter	0.2		
	Sprayer	1		
	Mower	0.6		
	Chopper	0.6		
G6	Tillage	0.6	KBS field data	
	Tractor	2		
	Sprayer	0.8		
	Fertilizer Applicator	0.2		
	Chopper	1		
	Cultivator	0.4		Used to disk rhizomes during planting, not additional tillage
G7	Tillage	0.6	KBS field data	
	Tractor	1.4		
	Sprayer	0.6		
	Mower	0.6		
	Chopper	0.6		
	Planter	0.2		
G9	Tillage	0.2	KBS field data	
	Tractor	1		
	Sprayer	0.8		
	Mower	0.6		
	Chopper	0.4		
G10	Tillage	0.4	KBS field data	
	Tractor	1		
	Mower	0.6		
	Chopper	0.6		

Material and Energetic Output

Table 12. KBS: Yield refers to grain yield at standard moisture content for corn, soybeans, canola; dry biomass yield of perennial crops. Per reference flow 1 ha $year^{-1}$.

System	Yield (Mg ha^{-1})	Potential Energy (MJ ha^{-1})	Source	Notes
G1	9.16	74780.67	KBS field data	corn ethanol energy [1]
corn-rot	8.15	66530.07		corn ethanol energy [1]
soybean-rot	2.67	18500.86		soybean biodiesel energy [2]
canola-rot	1.18	18919.14		canola biodiesel energy [3]
G5	2.98	19056.40		equation [4]
G6	8.65	55199.40		equation [4]
G7	1.98	12667.46		equation [4]
G9	2.17	13876.94		equation [4]
G10	1.67	10682.08		equation [4]

Soil Carbon Accumulation

Table 13. KBS: Carbon dioxide accumulation in the soil for each cropping system. Negative values indicate a net mitigation. Source: Gelfand et al., 2014.

Cropping System	g CO_2 m^{-2} yr^{-1}	kg CO_2 ha^{-1} yr^{-1}	KBS LTER Cropping System (and Assumptions)
G1 Continuous Corn	-88	-880	System: Corn-soybean-wheat rotation (Assumed 2008 was conventional due to tillage at experiment establishment. 2009-2012 was no-till.)
corn-rot			
soybean-rot			
canola-rot			
rotational system			
G5 Switchgrass	-161	-1610	System: Alfalfa
G6 Miscanthus			(Alfalfa was the only perennial monoculture system in LTER experiment; switchgrass and miscanthus are perennial monocultures)
G7 Native Grass mix	-220	-2200	System: Early Successional Community (Recently converted cropland; low input systems similar to this experiment)
G9 Old Field			
G10 Prairie Grass mix			

Nitrous Oxide Emissions

Table 14. KBS: Nitrous oxide emissions from each cropping system. Source: 4.3, in press.

Cropping System	**kg N_2O-N ha^{-1} yr^{-1}**	**kg N_2O ha^{-1} yr^{-1}**	**Notes**
G1 Continuous Corn	5.4849	8.6191	Measurements taken from reps 1-4 only. No measurements were taken from rep 5. Years: 2008 - starting in June 2009 2010 – data from only 3 reps for G7 and G10 2011 (2012 data unavailable)
corn-rot	3.9521	6.2104	
soybean-rot	0.9334	1.4668	
canola-rot	1.6856	2.6487	
rotational system	2.3792	3.7388	
G5 Switchgrass	1.5362	2.4140	
G6 Miscanthus	1.9284	3.0304	
G7 Native Grass mix	2.1031	3.3047	
G9 Old Field	1.2748	2.0033	
G10 Prairie Grass mix	0.8962	1.4082	

Equipment

Table 15. Farm equipment used in field experiment.

Equipment	Year	G1	corn-rot	soybean-rot	canola-rot	G5	G6	G7	G9	G10
Tractors										
John Deere 7420	2008									
	2009									
	2010									
	2011									
	2012				(not planted)					
John Deere 7330	2008									
	2009									
	2010									
	2011									
	2012				(not planted)					
Tillage Implements										
John Deere 726 15' 9" soil finisher	2008									
	2009									
	2010									
	2011									
	2012				(not planted)					
John Deere 970 12' cultimulcher	2008									
	2009									
	2010									
	2011									
	2012				(not planted)					
Case IH 183 S-tine 6 row cultivator	2008									
	2009									
	2010									
	2011									
	2012				(not planted)					
Planters										
John Deere 1730 Maxemerge Plus Planter	2008									
	2009									
	2010									
	2011									
	2012									
John Deere 750 no-till drill	2008									
	2009									
	2010									
	2011									
	2012				(not planted)					

Table 15 (cont'd)

John Deere 450 conventional 10' drill	2008									
	2009									
	2010									
	2011									
	2012				(not planted)					
Spraying and Fertilizer Equipment										
Demco 3-point mounted sprayer	2008									
	2009									
	2010									
	2011									
	2012				(not planted)					
8002 flat fan nozzle	2008									
	2009									
	2010									
	2011									
	2012				(not planted)					
Top Air Sprayer	2008									
	2009									
	2010									
	2011									
	2012				(not planted)					
TurboTeeJet 11003 flat fan nozzle	2008									
	2009									
	2010									
	2011									
	2012				(not planted)					
Gandy Orbit-Air 30' boom	2008									
	2009									
	2010									
	2011									
	2012				(not planted)					
six row fertilizer applicator	2008									
	2009									
	2010									
	2011									
	2012				(not planted)					
Harvest Equipment										
John Deere 9410 Combine	2008									
	2009									
	2010									
	2011									
	2012				(not planted)					
Swift 5' plot swather	2008									
	2009									
	2010									
	2011									
	2012				(not planted)					
John Deere 115 15' flail mower	2008									
	2009									
	2010									
	2011									
	2012				(not planted)					
John Deere 7350 self-propelled forage harvester	2008									
	2009									
	2010									
	2011									
	2012				(not planted)					
John Deere 676 forage head	2008									
	2009									
	2010									
	2011									
	2012				(not planted)					
John Deere 3430 12' haybine	2008									
	2009									
	2010									
	2011									
	2012				(not planted)					

Arlington Agricultural Research Station

Material Inputs

Table 16. Material inputs at ARL per reference flow of 1 ha year^{-1}.

System	Material Input	Value (kg ha^{-1})	Source	Notes
G1	seeds	23.76	WI field data	
	(5-14-42) starter fertilizer	-		broken down to 12.2 kg (46-0-0), 78.64 kg (0-0-60), 34.18 kg (0-46-0)
	(46-0-0) urea	43.45		
	(28-0-0) urea ammonium nitrate	381.86		
	(0-0-60) potash	186.02		
	dolomitic lime (80-89)	718.85		
	(0-46-0) triple super phosphate	38.09		
	(18-46-0) diammonium phosphate	2.69		
	ammonium sulphate	1.88		
	pesticides (total)	6.15		Herbicides: glyphosate; s-metolachlor; 2,4-D ester; mesotrione; simazine; tembotrione; MSO Pesticises: Force 3G; Prozap
	diesel	28.78	Stein, 2012	
corn-rot	seed	23.79	WI field data	
	(5-14-42) starter fertilizer	-		broken down to 12.2 kg (46-0-0), 78.64 kg (0-0-60), 34.18 kg (0-46-0)
	(46-0-0) urea	77.31		Corn phase data from: G2-2008 G2-2011 G2-2012 G3-2010 G3-2012 G4-2009
	(28-0-0) urea ammonium nitrate	396.47		
	(0-0-60) potash	193.17		
	(18-46-0) diammonium phosphate	22.46		
	(0-46-0) triple superphosphate	34.17		
	dolomitic lime (80-89)	599.04		
	ammonium sulphate	1.38		
	herbicide (total)	7.26		
	diesel	28.39	Stein, 2012	
soybean-rot	seed	122.20	WI field data	over-planting G3-2011 caused an inflated value
	(0-0-60) potash	26.73		Soybean phase data from: G2-2009 G3-2008 G3-2011 G4-2010 G4-2012
	dolomitic lime (80-89)	718.85		
	ammonium sulphate	3.16		
	herbicide (total)	9.56		
	diesel	28.78	Stein, 2012	

Table 16 (cont'd)

canola-rot	seed	6.46	WI field data	Canola phase data from: G2-2010 G3-2009 G4-2008 G4-2011
	(34-0-0) ammonium nitrate	115.54		
	(46-0-0) urea	79.36		
	(0-0-60) potash	34.82		
	dolomitic lime (80-89)	898.56		
	ammonium sulphate	3.14		
	herbicide (total)	5.73		
	diesel	28.31	Stein, 2012	
G5	seed	9.88	WI field data	seeded in 2008, 2009, and 2012
	(34-0-0) ammonium nitrate	99.74		Herbicides: 2,4-D; glyphosate; quinclorac; dicamba
	dolomitic lime (80-89)	718.85		
	herbicide (total)	5.78		
	diesel	32.52	Stein, 2012	
G6	rhizomes	-	WI field data	see assumptions
	(34-0-0) ammonium nitrate	166.79		Herbicides: dual II magnum; 2,4-D ester; glyphosate; prowl; dicamba; activator
	dolomitic lime (80-89)	718.85		
	herbicide (total)	7.84		
	diesel	29.79	Stein, 2012	
G7	seed	1.79	KBS field data	seed information was missing from field data
	(34-0-0) ammonium nitrate	99.74	WI field data	
	dolomitic lime (80-89)	718.85		
	herbicide (total)	2.738		Herbicides: glyphosate; 2,4-D ester
	diesel	32.29	Stein, 2012	
G9	(34-0-0) ammonium nitrate	99.74	WI field data	
	(46-0-0) urea	24.484		
	dolomitic lime (80-89)	718.85		
	diesel	28.39	Stein, 2012	
G10	seed	1.79	KBS field data	seed information was missing from field data
	dolomitic limestone	718.85	WI field data	
	herbicide (total)	0.856		Herbicide: glyphosate
	diesel	32.21	Stein, 2012	

Non-Material Inputs

Table 17. Non-material inputs at ARL per reference flow of 1 ha $year^{-1}$.

System	Non-Material Input	Number of trips across plot)	Source	Notes
G1	tractor	6.2	WI field data	
	sprayer	4.4		
	planter	1		
	tillage	0.8		
	combine	1		
corn-rot	tractor	5.5	WI field data	
	sprayer	4.5		
	planter	1		
	tillage	0.67		
	combine	1		
soybean-rot	tractor	5.2	WI field data	
	sprayer	3.4		
	planter	1.2		
	tillage	0.8		
	combine	1		
canola-rot	tractor	4	WI field data	
	sprayer	2.5		
	planter	0.75		
	tillage	1.5		
	combine	2.5		
G5	tractor	3.8	WI field data	
	sprayer	2.2		
	tillage	0.8		
	rotary mower	0.2		
	chopper	0.8		
	planter	0.6		
G6	tractor	3.4	WI field data	
	sprayer	2.6		
	haybine	0.6		
	tillage	0.8		
	chopper	0.6		
G7	tractor	2.8	WI field data	
	tillage	0.8		
	sprayer	1.6		
	mower	0.2		
	planter	0.8		
	chopper	1		
G9	tractor	1	WI field data	
	sprayer	1		
	chopper	1		
	haybine	1		
G10	tractor	2.2	WI field data	
	tillage	1		
	sprayer	1		
	mower	0.2		
	planter	0.2		
	chopper	0.8		

Material and Energetic Output

Table 18. ARL: Yield refers to grain yield at standard moisture content for corn, soybeans, canola; dry biomass yield of perennial crops. Per reference flow 1 ha $year^{-1}$.

System	Yield (Mg ha^{-1})	Potential Energy (MJ ha^{-1})	Source	Notes
G1	12.19	99522.12	WI field data	corn ethanol energy [1]
corn-rot	11.82	96500.60		corn ethanol energy [1]
soybean-rot	3.92	27207.50		soybean biodiesel energy [2]
canola-rot	1.82	29343.53		canola biodiesel energy [3]
G5	4.62	29473.32		equation [4]
G6	4.35	27765.88		equation [4]
G7	3.82	24362.47		equation [4]
G9	2.79	17807.75		equation [4]
G10	3.37	21526.30		equation [4]

Nitrous Oxide Emissions

Table 19. ARL: Nitrous oxide emissions from each cropping system. Source: 4.3, in press.

Cropping System	kg N_2O-N ha^{-1} yr^{-1}	kg N_2O ha^{-1} yr^{-1}	Data Years
G1 Continuous Corn	4.8270	7.5853	Years: 2008 - 2 time points only 2009 - miscanthus didn't overwinter; may have cause inaccuracies in G6 data 2010 2011 2012
corn-rot	5.3187	8.3580	
soybean-rot	2.6463	4.1585	
canola-rot	2.6782	4.2086	
rotational system	3.7238	5.8517	
G5 Switchgrass	4.0282	6.3300	
G6 Miscanthus	2.1941	3.4479	
G7 Native Grass mix	2.5905	4.0708	
G9 Old Field	1.8647	2.9302	
G10 Prairie Grass mix	2.6182	4.1144	

General Assumptions and GaBi 6.0 Model Assumptions

General Assumptions

Models relied on the intrinsic values included in the *Professional + Extension 2002* database within GaBi 6.0 for all other input and output values associated with material and non-material inputs and outputs that are not listed in above tables .

The switchgrass biomass conversion equation [4] was used for the biomass to energy conversions for G7 Native Grass Mix, G9 Old Field, and G10 Prairie Grass Mix.

Every material and/or non-material input was applied equally across entire plot area in time.

Every material and/or non-material output was harvested or released equally across entire plot area in time.

Gases, sequestered and/or emitted, were sequestered or emitted equally across entire plot area in time.

Unit processes and aggregated processes (LCI results) from the United States were used whenever available in the *Professional + Extension 2002* database within GaBi 6.0. When United States derived processes were unavailable, models were built with processes derived from Canada due to the close geographical proximity and relatively similar infrastructure between countries. When United States and Canada derived processes were unavailable in the *Professional + Extension 2002* database within GaBi 6.0, European, particularly German, derived processes were used in the cropping system models.

Equipment was not documented for Arlington Agriculture Research Station location. Equipment was assumed to be the same at both locations, therefore Kellogg Biological Station equipment was used for this missing information.

GaBi Model Unit Process Assumptions

Miscanthus

No appropriate model was present in the *Professional + Extension 2002* GaBi 6.0 database or could be created to approximate miscanthus rhizomes. Rhizomes were not included within the model due to these limitations.

No planting information was included for miscanthus planting at either location. Miscanthus was hand planted. Hand planting was not replicable in the GaBi model.

Corn and Corn in Rotation (corn-rot)

Biomass remaining in field after grain harvest (stover) was not modeled due to the limitations imposed by the software.

Nitrous Oxide Flux Data

There was incomplete nitrous oxide gas flux data for 2008 at both sites:

In 2008, the AARS fluxes are calculated from 2 (rather than the now-standard 4) time points. The available data was used in the models with no modifications.

In 2008, KBS did not start monitoring until June instead of at the beginning of the growing season. The available data was used in the models with no modifications.

In 2009, the majority of the miscanthus at Arlington Agricultural Research Station didn't overwinter so flux data may not be reliable for that location year. The available data was used in the models with no modifications.

In 2012, no data was available for KBS. The four-year average (2008, 2009, 2010, 2011) was used in place of a five-year average value in the models with no modifications.

Energy Conversions

Corn Grain Ethanol

corn grain yield in Mg per hectare × covert to kg × litres per kg of corn grain* × density of ethanol × energy per liter of ethanol × convert to MJ = energy per hectare

$$\text{corn grain yield } \frac{Mg}{ha} \times \frac{1000\ kg}{1\ Mg} \times \frac{1\ litre}{2.6\ kg\ grain} \times \frac{0.789\ kg}{1\ litre} \times \frac{26{,}900\ kJ}{1\ kg} \times \frac{1\ MJ}{1000\ kJ} = \frac{MJ}{ha} \quad [1]$$

*conversion factor: Pimental, 2001.

Soybean Biodiesel

soybean yield in Mg per hectare × convert to kg × convert to pounds × pounds per bushel of soybeans × gallons of biodiesel per bushel* × energy per gallon of biodiesel × convert to MJ = energy per hectare

$$\text{soybean yield } \frac{Mg}{ha} \times \frac{1000\ kg}{1\ Mg} \times \frac{2.2\ lbs}{1\ kg} \times \frac{1\ bu}{60\ lbs} \times \frac{1.5\ gallons}{1\ bu} \times \frac{119500\ btu}{1\ gallon} \times \frac{1\ MJ}{947.817120313\ btu} = \frac{MJ}{ha}$$

[2]

*conversion factor: Pradhan et al. 2009.

Canola Biodiesel

$$\text{canola yield in Mg per hectare } \times \text{ convert to kg } \times \text{ conver to pounds } \times \text{ pounds per bushel of canola } \times \text{ gallons of biodiesel per bushel* } \times \text{ energy per gallon of biodiesel } \times \text{ convert to MJ} = \text{energy per hectare}$$

$$\text{canola yield } \frac{Mg}{ha} \times \frac{1000\ kg}{1\ Mg} \times \frac{2.2\ lbs}{1\ kg} \times \frac{1\ bu}{50\ lbs} \times \frac{2.9\ gallons}{1\ bu} \times \frac{119500\ btu}{1\ gallon} \times \frac{1\ MJ}{947.817120313\ btu} = \frac{MJ}{ha}$$

[3]

*conversion factor: McIntosh et al. 1983.

Switchgrass Cellulosic Ethanol

biomass yield in Mg per hectare × convert to tons × gallons per ton of switchgrass*

× convert to litres × convert to kg

× energy per litre of ethanol × convert to MJ = energy per hectare

$$\text{biomass yield } \frac{Mg}{ha} \times \frac{1\ ton}{0.90718\ Mg} \times \frac{72\ gallons}{1\ ton} \times \frac{3.78541\ litres}{1\ gallon} \times \frac{0.789\ kg}{1\ litre} \times \frac{26900\ kJ}{1\ kg} \times \frac{1\ MJ}{1000\ kJ} = \frac{MJ}{ha} \qquad [4]$$

*conversion factor: from Morrow et al. 2006.

Corn Stover Cellulosic Ethanol

biomass yield in Mg per hectare × convert to tons × gallons per ton of stover*

× convert to litres × convert to kg

× energy per litre of ethanol × convert to MJ = energy per hectare

$$\text{biomass yield } \frac{Mg}{ha} \times \frac{1\ ton}{0.90718\ Mg} \times \frac{80\ gallons}{1\ ton} \times \frac{3.78541\ litres}{1\ gallon} \times \frac{0.789\ kg}{1\ litre} \times \frac{26900\ kJ}{1\ kg} \times \frac{1\ MJ}{1000\ kJ} = \frac{MJ}{ha} \qquad [5]$$

*conversion factor from: Sheaffer et al. 2010.

REFERENCES

REFERENCES

Bare, Jane C. “Developing a consistent decision-making framework by using the US EPA’s TRACI.” Cincinnati, Ohio, USA: US Environmental Protection Agency (2002).

Bare, J.C., Norris, G.A., Pennington, D.W., and T. McKone. “TRACI: The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts”. Journal of Industrial Ecology (2003). 6:3-4.

Bessou, Cécile, et al. “Using a crop model to account for the effects of local factors on the LCA of sugar beet ethanol in Picardy region, France.” The International Journal of Life Cycle Assessment 18.1 (2013): 24-36.

Brentrup, P., and C. Palliere. 2008. “GHG emissions and energy efficiency in European nitrogen fertiliser production and use. Proc: International Fertiliser Society, December 11, York, UK.

Caffrey, Kevin R., and Matthew W. Veal. “Conducting an Agricultural Life Cycle Assessment: Challenges and Perspectives.” The Scientific World Journal 2013 (2013).

Carson, Walter P., and Gary W. Barrett. “Succession in old-field plant communities: effects of contrasting types of nutrient enrichment.” Ecology 69.4 (1988): 984-994.

Congressional Research Service. 2013. “Renewable Fuels Standard: Overview and Issues.” March 14. www.fas.org/sgp/crs/misc/R40155.pdf (accessed April 11, 2014).

Drapcho, C.M.; Nghiem, N.P.; Walker, T.H. Biofuels Engineering Process Technology; McGraw-Hill: New York, NY, USA, 2008.

Gelfand, I. and G. P. Robertson. 2014. Mitigation of Greenhouse Gases in Agricultural Ecosystems. Pages forthcoming. S. K. Hamilton, J. E. Doll, and G. P. Robertson, editors. The ecology of agricultural ecosystems: long-term research on the path to sustainability. Oxford University Press, New York, New York, USA.

Great Lakes Bioenergy Research Center. 2014. “Experimental Layouts.” data.sustainability.glbrc.org (accessed April 11, 2014).

Great Lakes Bioenergy Research Center. 2014. “GLRBC - About”. www.glbrc.org/about (accessed April 11, 2014).

Hedtcke, J.L., G.R. Sanford, K.E. Hadley, and K.D. Thelen. 2014. Maximizing land use during switchgrass establishment in the North Central United States. Agron J. 106:596-604.

Huang, Ying, Yaying Li, and Huaiying Yao. “Nitrate enhances N2O emission more than ammonium in a highly acidic soil.” Journal of Soils and Sediments 14.1 (2014): 146-154.

Hutchinson, G.L., Mosier, A.R., 1981. Improved Soil Cover Method for Field Measurement of Nitrous Oxide Fluxes. Soil Sci. Soc. Am. J. 45, 311. doi:10.2136/sssaj1981.03615995004500020017x

Intergovernmental Panel on Climate Change (IPCC). 2007. “2.10.2 Direct Global Warming Potentials.” http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-10-2.html (accessed April 16, 2014).

Kaltschmitt, M., Reinhardt, G.A., and T. Stelzer. Life cycle analysis of biofuels under different environmental aspects. Biomass and Bioenergy (1997); 12:121-34.

Kendall, A. and J. Yuan. “Comparing life cycle assessments of different biofuel options.” Current Opinion in Chemical Biology (2013); 17:439-443.

Lemke, Reynald, and Rich Farrell. “Nitrous Oxide Emissions and Prairie Agriculture.” Prairie Soils and Crops 1 (2008): 11-15.

Livingston, G., Hutchinson, G.P., 1994. Enclosure-based measurement of trace gas exchange: applications and sources of error, in: Matson, P.A., Harriss, R.C. (Eds.), Biogenic Trace Gases: Measuring Emissions from Soil and Water. Blackwell Scientific, London, pp. 14 – 51.

Lohbeck, Madelon, et al. “Changing drivers of species dominance during tropical forest succession.” Functional Ecology (2014).

McIntosh, Christopher S., Stephen M. Smith, and Russell V. Withers. “Energy balance of on-farm vegetable oil production and extraction in selected areas of Idaho and Washington.” Research Bulletin, Idaho Agricultural Experiment Station 129 (1983).

Menten et al. “A review of LCA greenhouse gas emissions results for advanced biofuels: The use of meta-regression analysis.” Renewable and Sustainable Energy Reviews 2013

Michigan State University Enviro-weather. 2014. “Enviro-weather.” www.agweather.geo.msu.edu /mawn/sation.asp?id=kbs (accessed April 8, 2014).

Morrow, William R., W. Michael Griffin, and H. Scott Matthews. “Modeling switchgrass derived cellulosic ethanol distribution in the United States.” Environmental Science & Technology 40.9 (2006): 2877-2886.

ISO, EN. “14040: 2006.” Environmental management-Life cycle assessment-Principles and framework. European Committee for Standardization (2006).

ISO, EN. “14044: 2006.” Environmental management-Life cycle assessment-Requirements and guidelines. European Committee for Standardization (2006).

National Climatic Data Center. “1981-2012 Normals Data Access.” http://www.ncdc.noaa.gov/land-based-station-data/climate-normals/1981-2010-normals-data (accessed April 18, 2014).

National Weather Service. 2014. “National Weather Service Forecast Office.” www.nws.noaa.gov/ climate (accessed April 8, 2014).

Oates et al. “Nitrous oxide emissions from model biofuel cropping systems in the establishment phase.” (working title 2014).

Parkin, T.B., and Rodney T. Venterea. “USDA-ARS GRACEnet Project Protocols Chapter 3. Chamber-Based Trace Gas Flux Measurements 4.” Sampling Protocols. USDA-ARS, Fort Collins, CO (2010): 3-1.

Pimentel, David. “Biomass utilization, limits of.” Encyclopedia of physical science and technology 2 (2001): 159-171.

Pradhan, A., Shrestha, D.S., McAloon, A., Yee, W., Hass, M., Duffield, J.A., and H. Shapouri “Energy life-cycle assessment of soybean biodiesel.” United States, Department of Agriculture, Agricultural Economic Report 845 (2009).

Renewable Fuels Association. 2014. “Industry Resources: Co-products.” www.ethanolrfa.org/pages/industry-resources-coproducts (accessed April 14, 2014).

Robertson, G.P., E.A. Paul, and R. R. Harwood. “Greenhouse gases in intensive agriculture: contributions of individual gases to the radiative forcing of the atmosphere.” Science 289.5486 (2000): 1922-1925.

Sheaffer, C., J. Lamb, and C. Rosen. “Corn Stover: Ethanol Production and Nutrient Uptake.” December 2010. www.mncorn.org/.../mncorn.../B6-CornStoverEthanolProduction_2.pdf. (accessed April 29, 2014).

Skowroñska, Monika, and Tadeusz Filipek. “Life cycle assessment of fertilizers: a review.” Int Agrophys 28 (2014): 101-110. doi: 10.2478/intag-2013-0032.

Smith, K.A., Dobbie, K.E., 2001. The impact of sampling frequency and sampling times on chamber-based measurements of N2O emissions from fertilized soils. Glob. Chang. Biol. 7, 933–945. doi:10.1046/j.1354-1013.2001.00450.x.

Stein, D. 2012. 2013 Custom Machine and Work Rate Estimates. Michigan State University Extension.

Toma, Yo, et al. “Nitrous oxide emission derived from soil organic matter decomposition from tropical agricultural peat soil in central Kalimantan, Indonesia.” Soil science and plant nutrition 57.3 (2011): 436-451.

U.S. Department of Energy. 2011. U.S. Billion-ton update: Biomass supply for a bioenergy and bioproducts industry. R.D. Perlack and B.J. Stokes, editors, ORLN/TM-2011/224. Oak Ridge Natl. Lab., Oak Ridge, TN. 227p. http://info.ornl.gov/sites/publications/files/Pub31057.pdf (accessed 28 Oct. 2013).

Wright, L. “Historical perspective of how and why switchgrass was selected as a “model” high-potential energy crop”. 2007.

CHAPTER 2

MAXIMIZING LAND USE DURING SWITCHGRASS ESTABLISHMENT IN THE NORTH CENTRAL UNITED STATES

Reprinted by Permission, ASA, CSSA, SSSA. A reformatted version of this chapter was published in the Agronomy Journal as: Hedtcke, J.L., G.R. Sanford, K.E. Hadley, and K.D. Thelen. 2014. Maximizing land use during switchgrass establishment in the North Central United States. Agron J. 106:596-604.

Abstract: Switchgrass (*Panicum virgatum* L.) grown under three differing establishment methods was evaluated for yield, quality, and potential ethanol production across seven environments in Wisconsin and Michigan. The three establishment methods included: (i) June seeding into fallow ground; (ii) June seeding following winter rye (*Secale cereale* L.) forage; and (iii) August seeding following winter wheat (*Triticum aestivum* L.). Planting switchgrass in June was successful following the rye forage crop, but planting in August after wheat resulted in complete stand loss. While harvested biomass in a two-cut system was equal to or greater than that realized in a one-cut system (6.9 vs. 6.8 Mg ha^{-1}), biomass quality for ethanol production was highest following a killing frost (226 vs. 224 g ethanol kg^{-1} biomass). The higher overall biomass production in the two-cut system generally compensated for this difference however, with ethanol yields similar between the two systems (1950 vs. 1970 L ethanol ha^{-1} for the two- and one-cut system, respectively). In addition to ethanol production, we found that forage nutritive value in the first cut of the two-cut system was of sufficient quality to satisfy the dietary needs of several classes of livestock. Harvesting established switchgrass for hay with an early season cutting in a two-cut system provides producers with an alternative forage source

while not affecting total seasonal biomass yield if harvested at the appropriate growth stage and cutting height to leave sufficient photosynthetic material for regrowth.

INTRODUCTION

Ethanol and other biofuels have the potential to replace 30% or more of the gasoline demand in the United States by 2030 (U.S. Department of Energy, 2011). Presently, the majority of domestic ethanol comes from corn (*Zea mays* L.) grain, but the long-term sustainability of grain ethanol is questionable as it may increase competition between food, feed, and fuel interests (USDA-ERS, 2013). Switchgrass has been identified as a candidate bioenergy crop in recent decades by the U.S. Department of Energy, particularly as a second-generation feedstock for conversion to liquid fuels (Monti, 2012). Recent advances in cellulosic conversion technology and the development of large-scale cellulosic ethanol production facilities have made switchgrass a viable alternative to corn grain ethanol (McLaughlin et al., 2002). Switchgrass is attractive as a biofuel crop because of its adaptability from Canada to Texas, its ability to grow on marginal, highly erodible, and drought-prone soils, and its environmental benefits which include C sequestration and wildlife habitat (McLaughlin and Walsh, 1998). It can also be grown and harvested using existing forage production equipment, reducing potential barriers to farmer adoption.

A significant number of producers surveyed in Tennessee and Illinois indicated that as production technology and technical assistance become increasingly available, and as demand creates a viable market for biomass, they would be interested in growing switchgrass on their farms (Sanderson et al., 2012). They may, however, be hesitant to do so if income losses cannot be offset during the slow establishment period of switchgrass. Although switchgrass can be harvested in as little as 2 years from establishment (Vogel et al., 2002), it may not reach its full yield potential until the third growing season in the colder climates of the north central United States. Economically feasible systems must therefore be designed which can carry a producer through the critical establishment period. The purpose of this study was threefold and sought to: (i) evaluate two cropping options with small grains (winter rye and winter wheat) from which farmers could realize economic gains during the establishment phase of switchgrass while not reducing subsequent switchgrass productivity; (ii) to evaluate the potential tradeoffs of switchgrass managed as a dedicated bioenergy crop (October harvest) vs. a dual-use feed and biomass crop (two cuts; June and October); and (iii) to determine the quality of biomass and theoretical ethanol yield produced under the one-cut and two-cut harvest management strategies. Our initial three hypotheses were that: (H_1) A rye forage crop preceding switchgrass establishment would depress switchgrass yields compared to that following a fallow phase; (H_2) Planting switchgrass in early June (following fallow or rye) would provide a better stand than planting in August (following winter wheat); and (H_3) Late-season biomass from the two-harvest management system would be of equal or higher quality than the late-season biomass from the one-harvest management system in terms of cattle (*Bos taurus*) feed and theoretical ethanol yield.

MATERIALS AND METHODS

Treatments, Experimental Design, and Site Description

Switchgrass yields were evaluated in both the seeding year and first production year under three treatments. The three treatments consisted of different crop establishment methods and included switchgrass planting: (i) in June, fallow since previous fall (control treatment); (ii) in June, following a winter rye forage crop; and (iii) in August, following wheat harvested for grain and straw. The experimental design was a randomized complete block, with four replicates. To experience a wider range of seasonal rainfall and temperature patterns, as well as different soil types and field management, the trial was initiated seven times at various locations. All sites had been in field crop rotations for several years before the study (Table 1). For most sites, the April to August rainfall was above average in 2010 and below average in 2011. In the fall of 2009, three sites in southern Wisconsin (Arlington [ARL], Rio [RIO], and Sugar Creek [SC]) were established. In the fall of 2010, three more sites nearby or adjacent to the 2009 fields plus an additional site in southwest Michigan (Kellogg Biological Station, KBS) were added. The combination of site and year were merged into one variable referred to as "environment". Soils were assessed for fertility before the start of the trial at each environment and were all in an "optimum" range for switchgrass production based on University of Wisconsin-Extension recommendations (Laboski and Peters, 2012). Soil test phosphorus (STP), soil test potassium (STK), organic matter (OM), and pH status along with other basic site characteristics are shown in Table 1. All environments were managed with no-till practices except SC-I and SC-II.

Table 20. Site characteristics from seven environments in southern Wisconsin and lower Michigan.

		Location						
	Site characteristics	Arlington, WI†		Rio, WI‡		Sugar Creek, WI‡		Hickory Corners, MI†
	Environment	ARL-I	ARL-II	RIO-I	RIO-II	SC-I	SC-II	KBS-I
	Longitude	89°22′54″ W	89°22′25″ W	89°11′47″ W	89°11′55″ W	89°38′48″ W	89°38′48″ W	85°22′35″ W
	Latitude	43°17′50″ N	43°17′27″ N	43°28′49″ N	43°28′49″ N	42°42′50″ N	42°41′40″ N	42°23′44″ N
	Seeding year	2010	2011	2010	2011	2010	2011	2011
	Previous crop§	alfalfa/grass	soybean	soybean	soybean	ryegrass	ryegrass	grass
	Plot size	6 by 27 m	9 by 30 m	9 by 30 m	9 by 30 m	12 by 15 m	12 by 15 m	4.5 by 15 m
Soil properties	Texture	Silt loam	Silt loam	Sandy loam	Sandy loam	Silt loam	Silt loam	Loam
	USDA soil series	Plano	Huntsville	Wyocena/ Plainfield	Wyocena/ Plainfield	Miami	Miami	Kalamazoo
	Slope	0–2%	0–2%	2–6%	2–6%	2–6%	2–6%	2–6%
	pH	6.9	6.9	6.6	6.6	7.3	7.1	6.3
		g kg^{-1}						
	OM¶	40.0	39.0	15.0	15.0	24.0	25.0	19.0
		mg kg^{-1}						
	STP#	98	80	37	34	59	75	41
	STK#	179	212	127	99	132	125	127

† Research plots located on University Research Station.
‡ Research plots located on private farms and co-managed with farmer-cooperator.
§ Soybean [*Glycine max* (L.) Merr.], rygrass (*Lolium* spp.).
¶ OM = soil organic matter determined by weight loss on ignition (http://uwlab.soils.wisc.edu/files/procedures/organic_matter.pdf).
# STP and STK = soil test phosphorus, and soil test potassium, respectively, obtained using the Bray P1 extract (http://uwlab.soils.wisc.edu/files/procedures/available_P.pdf, http://uwlab.soils.wisc.edu/files/procedures/available_K.pdf).

In addition to having a recent cropping history with good fertility (see Table 1), no major perennial weed issues existed which created ideal conditions for switchgrass establishment. In the established year of switchgrass (Year 2), a split plot was imposed over the three previous crop treatments (fallow, rye, wheat). Subplots consisted of two harvest managements: (i) a two-cut management system harvested once in June, targeted at early boot stage (R0 stage per Moore et al., 1991) and once again after the killing frost (S5 growth stage per Moore et al., 1991) and (ii) a one-cut management system, harvested after the killing frost (S5).

Small Grains Management

Winter rye and winter wheat were planted on the same day at each given environment according to UW-Madison extension best management practices using a conventional or no-till grain drill. While the winter wheat variety was the same at all environments (Pioneer 25R47), the rye varieties were chosen based on regional adaptation and differed by state (WI: cultivar Spooner, MI: cultivar Wheeler). Plot size averaged 9 by 30 m, large enough to accommodate field-scale planting and harvest equipment. Glyphosate (N-[phosphonomethyl] glycine) was applied at a rate of 0.95 kg a.e. ha^{-1} as a burndown treatment before seeding wheat and rye. Across the environments, a subsequent post emergence application of a broadleaf herbicide such as Harmony Extra XP (thifensulfuron-methyl [93 g a.i. ha^{-1}] + tribenuron-methyl [47 g a.i. ha^{-1}]) or 2,4-D (2,4-Dichlorophenoxyacetic acid [1.07 kg a.e. ha^{-1}]) was applied at the jointing leaf stage of wheat. Herbicide was not necessary in the winter rye treatment. The exception to herbicide use was the SC environments where no herbicide was used throughout the trial. The fallow treatment was not sprayed or tilled during the small grain phase. At most environments, N was applied to the wheat and rye treatments in early spring at 67 kg N ha^{-1} as urea. Being part of SC farm's overall management practices, manure was applied evenly across the field before planting the small grains at SC at an equivalent available N rate to the fertilizer used at other sites. Minimal effect of the residual manure nutrients was expected nor observed.

Winter rye forage was harvested at boot stage in mid-to-late May across environments to provide maximum total digestible nutrients (i.e., best combination of yield and nutrition) for livestock feed (McCormick et al., 2006). A center strip from each of the rye plots was cut with a self-propelled sickle bar mower set at a cutting height of 7.5 cm. After weighing the entire fresh sample on a pad scale, a grab sample of the forage was collected, weighed fresh, and dried at 60°C until it reached a constant weight to determine moisture content. Biomass is reported on a dry matter (DM) basis. Winter wheat was harvested for grain using field-scale combines in late July or early August. Wheat straw was removed from the field within 3 days of grain harvest at most environments other than at RIO where straw yields were minimal and therefore chopped and evenly redistributed back onto the field to maintain OM and STK.

Switchgrass Management

After the cereal crops were harvested, a burndown herbicide treatment of glyphosate (0.95 kg a.e. ha^{-1}) was applied to control weeds in all treatments at all environments except SC where tillage was used for weed control. A second burndown application was occasionally necessary just before switchgrass seedlings had emerged in the rye or fallow plots. An upland variety of switchgrass, cultivar Cave-in-Rock was seeded at a depth of 1.3 cm in 19-cm rows in mid-to-late June with a no-till drill at all sites with the exception of SC where a conventional grain drill was used. At all of the Wisconsin environments, the rate on the drill was set at 22 kg ha^{-1}. This rate was set approximately twice as high as the recommended rate to compensate for poor germination (12%) and a high percentage of hard seed (78%) in the seed lot purchased. A different seed lot, with higher germination (~80%), was planted at KBS and the grain drill was therefore set at 9 kg seed ha^{-1}.

Though the soil was not tested for residual nitrate N, it was decided not to apply any N during the switchgrass seeding year to discourage weeds and to limit unnecessary economic inputs (Mitchell et al., 2008; Renz et al., 2009; Sanderson and Reed, 2000). When the switchgrass reached the three to four leaf stage, that is, V3 to V4 per Moore et al. (1991) (late July/early August), 2,4-D (0.53 kg a.e. ha^{-1}) or a combination of Quinclorac (3,7-dichloro-8-quinolinacarboxylic acid [0.42 kg a.i. ha^{-1}]) and atrazine (2-chloro-4-[ethylamino]-6-

[isopropylamino]-s-triazene [0.12 kg a.i. ha^{-1}]) was used on the rye and fallow plots to control broadleaf weeds. The exception was at the SC environment where weeds were managed by clipping with a rotary mower. In the first production year of switchgrass, before emergence, a spring burndown treatment of glyphosate was applied across environments (except SC and KBS) to reduce weed pressure from winter annuals and cool-season grasses. A follow-up broadleaf herbicide application of 2,4-D at a rate of 0.53 to 1.07 kg a.e. ha^{-1} was made in late May or early across environments (except SC and KBS). No N was applied to the switchgrass in the production year other than at KBS where 79 kg N ha^{-1} was applied in June.

Forage Sampling

In the seeding year, three subsamples of switchgrass were collected from each experimental unit (i.e., plot) during peak biomass (late September) with hand shears and 0.5-m^2 quadrat. Weeds were sorted and separated from switchgrass and the biomass of each was recorded (no weed data from ARL-II and RIO-II). During the established phase (second year), three subsamples of switchgrass were collected from each of the 16 plots (four replicates × two previous crops × two harvest managements) with a 0.25-m^2 quadrat and hand shears at a 15-cm stubble height. The first cutting of the two-cut harvest treatment was sampled in June when the switchgrass reached boot stage (about 45–60 cm in height). This harvest strategy was based on the work of Vogel (2004) that demonstrated maximized seasonal switchgrass production and persistence under such management in Nebraska. As soon as possible after sampling in June, field-scale haying equipment removed the biomass from the “two-cut” system plots at a target cutting height of 15 cm. The second cutting in the two-cut system plots and the one-cut system plots were sampled after the killing frost (–3°C) in October. Samples were collected from the center of the plots to eliminate shading and border effects. Samples were then dried at 60°C, in a forced-air oven until constant mass was achieved. Results are reported on DM basis. Dry samples were ground through a 1-mm screen in a Thomas Wiley hammer mill (Arthur H. Thomas, Philadelphia, PA) and retained for subsequent polysaccharide analysis. The nutritive value and mineral composition of whole-plant switchgrass forage was analyzed on all samples at the University of Wisconsin Soil and Forage Analysis Laboratory (Marshfield, WI) using near infrared reflectance spectrophotometer (NIRSystem, Inc., Silver Spring, MD, model 6500) to predict the following quality parameters: crude protein (CP), neutral detergent fiber (NDF), and neutral detergent fiber digestibility (NDF-D). Whole-plant K was measured by atomic absorption spectroscopy (AOAC, 2008; Schulte et al., 1987).

Soil Moisture

Volumetric moisture content (VMC, g kg^{-1}) status of the soil was collected at a subset of environments (n = 4) that ranged most widely in soil type and seasonal moisture. Soil moisture was measured with a SpectrumTechnologies, Inc. (Aurora, IL) Field Scout 300 time domain reflectometer (TDR) probe on all treatments at two depths (12 and 20 cm) within 1 week after seeding (i.e., June and August) in four subsamples per plot. Data from ARL and RIO were used to compare soil type and effect of treatments on VMC in the two seasons.

Switchgrass Stand Frequency

Switchgrass establishment success was evaluated using the grid method (a grid of 25 cells of 0.15 cm^2 each) developed by Vogel and Masters (2001). Frequency counts were taken in the year after seeding to determine if seedlings overwintered and frequencies were above the 40% threshold level, which qualifies as a successful establishment, as determined by others (Hyder et al., 1971; Schmer et al., 2006). Two measurements were taken from each experimental unit in mid-July or early August when switchgrass was actively growing, but before it got too tall to effectively use the grid method.

Theoretical Ethanol Yield

The dried and ground switchgrass samples were sent to the Cell Wall Facility at Michigan State University for analysis. Acid hydrolysis with a weak acid was used to facilitate the separation of lignin, hemicellulose, and crystalline cellulose (Foster et al., 2010). The composition of hemicellulose was determined by an alditol acetate derivation of the soluble monosaccharides and quantified by gas chromatography-mass spectrometry (GC/MS) (Albersheim et al., 1967). Residue from the initial acid hydrolysis was washed with an Updegraff reagent and hydrolyzed with sulfuric acid; a colorimetric assay was used to determine the crystalline cellulose content of the residue (Updegraff 1969; Selvendran and O'Neill, 1987). The resulting glucose, xylose, and crystalline cellulose concentrations were used to calculate the predicted ethanol yield for each sample.

Theoretical ethanol yield was calculated based on the empirically derived hydrolyzable glucose and xylose levels using Eq. [6] below:

$$\{([Glc] + [Cry\ Cellu] \times Glc\ conv) + ([Xyl] \times Xyl\ conv)\} \times 51.1\% \times \text{ metabolic yield} = (\text{ethanol mg kg}^{-1}) \quad [6]$$

where [Glc] is the glucose concentration of the biomass following pretreatment and acid hydrolysis (mg kg^{-1}), [Xyl] is the xylose concentration of the biomass following pretreatment and acid hydrolysis (mg kg^{-1}), and [Cry] is the crystalline cellulose concentration of the biomass following pretreatment and acid hydrolysis (mg kg^{-1}). Glc conv is the glucan conversion (%) following enzymatic hydrolysis of feedstock material and Xyl conv is the xylan conversion (%) following a separate enzymatic hydrolysis and fermentation (SHF) of feedstock material. Glc and Xyl conversion values were determined from Jin et al. (2010), for switchgrass (66.5 and 74.7% for Glc and Xyl, respectively). The mass conversion of fermentable sugars to ethanol is 51.1%, and metabolic yield equals the ratio of ethanol to sugars consumed in the fermentation process divided by 51.1% (Lau and Dale, 2009). The metabolic yield value for switchgrass (89.7%) was determined using a SHF process and was derived from Jin et al. (2010). The theoretical ethanol yield was determined by multiplying the result from Eq. [5] with its corresponding dry matter yield.

Statistical Analysis

Analysis of switchgrass production, VMC, stand frequency, biomass quality, and theoretical ethanol yield were all conducted using PROC MIXED of SAS 9.1.3. The UNIVARIATE procedure (SAS 9.1.3) was used to confirm model assumption of normality and variance equality (SAS Institute, 2006; Littell et al., 2006). Kenward–Roger type degrees of freedom estimates were used per Gbur et al. (2012). In the mixed model for yield, stand frequency, biomass quality, and theoretical ethanol yield, both previous crop and harvest management were considered fixed effects, while environment (site-start combination), block, and their interaction terms were treated as random effects. Treating environment as a random effect increased the zone of inference for this study to include much of the North Central United States. Best linear unbiased predictors (BLUP’s) were used to evaluate the random effect of previous crop and harvest management treatments in individual environments (Littell et al., 2006). In the case of VMC, due to data from only two locations and 2 years, all terms in the model, with the exception of block, were treated as fixed. Statistical significance was based on an α level of 0.05 unless otherwise noted.

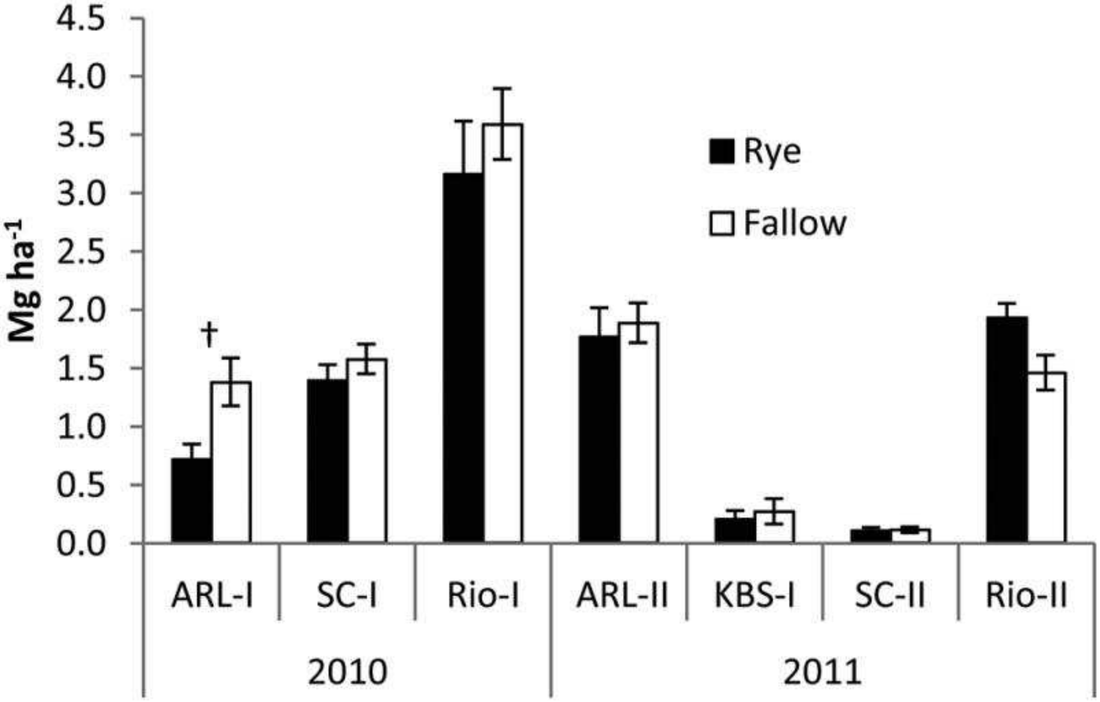
RESULTS AND DISCUSSION

Seeding Year Switchgrass

The August seeding of switchgrass failed as a result of winter kill at all seven environments despite successful germination and late season biomass establishment (∼10 cm of growth). Stand frequency 1 year after seeding averaged just 5.6% for this treatment. Competition from volunteer winter wheat, and the lack of time between planting and killing frost for root establishment likely contributed to the failed seeding. Furthermore, the morphological development of warm-season grasses in which the coleoptilar node is relatively short makes them relatively sensitive to the dry soil conditions commonly encountered during the late summer in the North Central United States (Hoshikawa 1969).

There was no effect of previous crop (fallow vs. rye) on seeding year switchgrass yields ($P = 0.3602$). In the successful treatments, switchgrass seeding-year yields ranged dramatically across environments from <0.11 Mg ha^{-1} to more than 3.37 Mg ha^{-1}. Poor weed control at SC combined with a dry summer in 2011 hindered switchgrass growth at that environment;

conversely, the consistent rainfall throughout 2010 and the warm sandy soils at RIO combined to provide ideal growing conditions for the switchgrass planting (Figure 39).



† P<0.10,* P<0.05, ** P<0.01,*** P<0.001

Figure 39. Seeding year switchgrass yields at each of the seven environments. Values represent the mean of four replicates, and error bars represent 1 standard error of the mean.

Weed control is especially important in a slow-establishing perennial such as switchgrass. There was no effect of previous crop on weed biomass within the switchgrass plots (P < 0.1318). Overall, weeds comprised about 30% the total seeding year biomass. As shown in Figure 39, at the SC-II environment where weeds were managed without herbicides in a very dry season, second year switchgrass production was depressed compared to the other environments that used herbicides in the seeding year.

Surface Soil Moisture

In 2010, a season with ample rainfall and an above average snowfall during the 2009/2010 winter, VMC at 12-cm depth was adequate (above permanent wilting point) and similar across all treatments and sampling times for each soil type (Figure 40). Striking differences were evident between years at RIO when June 2011 had much lower surface soil moisture than June 2010. The actively growing wheat treatment in the relatively dry spring of 2011 had lower VMC than the other treatments across soil types which may have been an additional factor in the failed switchgrass establishment. The rye treatment was above the permanent wilting point of 100 g kg^{-1} (Figure 40). Cover crops, especially cereal crops, are well documented for their ability to conserve soil moisture through reduced surface evaporation (Haramoto and Brainard, 2012; Krueger et al., 2011; Unger and Vigil, 1998). Decomposition of the rye roots may have also improved infiltration and water holding capacity of the soil, positively affecting early summer VMC readings as shown by other research (Gregory et al., 2005; Joyce et al., 2002; Lal et al., 1979; Troeh et al., 2004; Unger and Vigil, 1998). A recent survey of more than 700 growers in the central United States showed that cover crops were credited with a 10 to 14% improvement in water conservation and soil conditions compared to field without cover crops (USDA-SARE, 2013). In this same survey, winter cereal grains were the most common cover crop cited with more than 70% of respondents having reported using them.

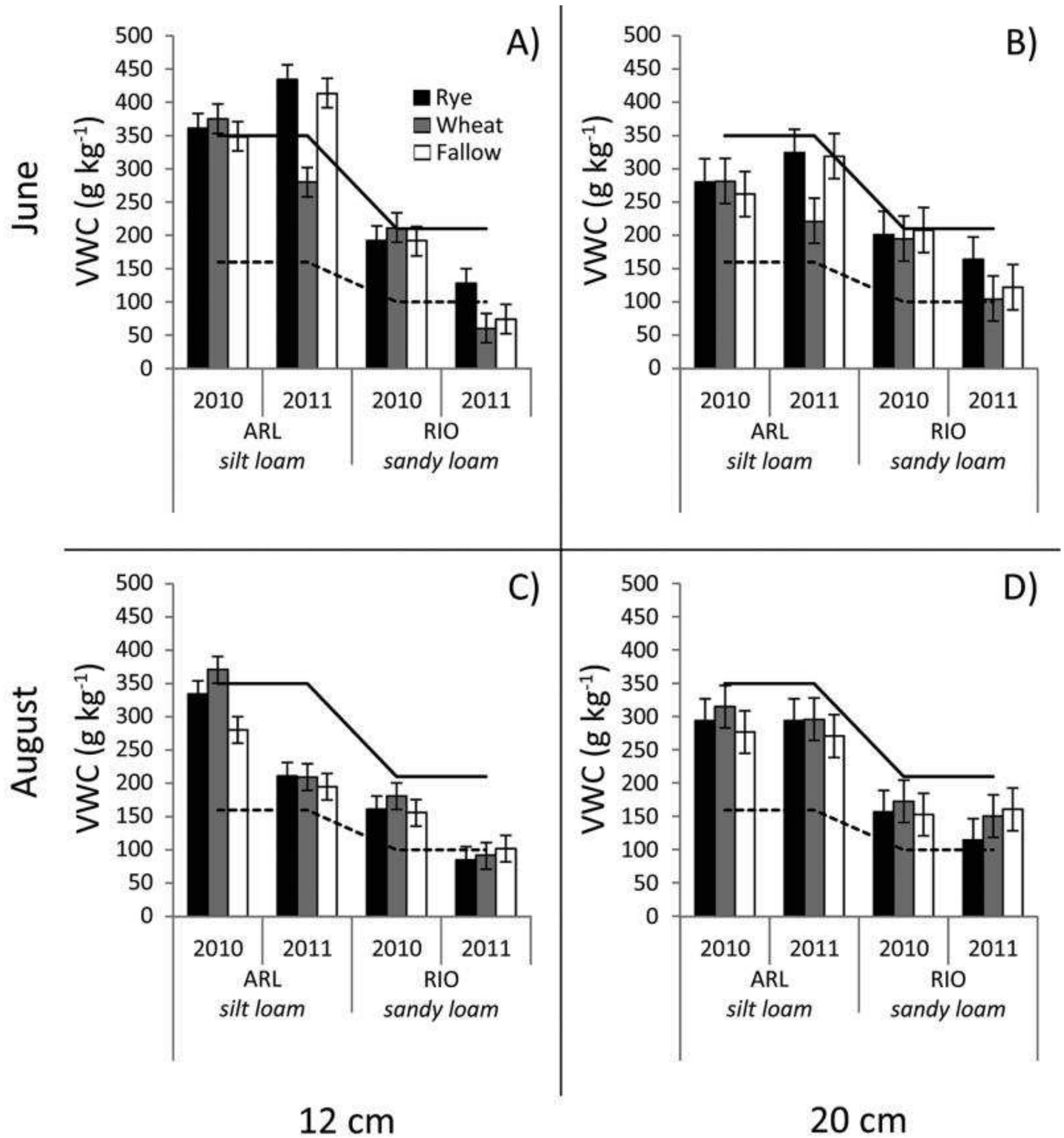


Figure 40. Volumetric water content Θ during the 2010 and 2011 growing seasons at: **A** 12 cm in June, **B** 20 cm in June, **C** 12 cm in August, and **D** 20 cm in August. Error bars represent the 95% confidence limit for comparison of Θ within a season and soil depth (e.g., A, B, C, **D**. Solid line represents field capacity; dotted line represents permanent wilting point for these soils.

Subsurface Soil Moisture

At the 20-cm depth, VMC had a similar pattern as it did at the 12-cm depth, with the exception that the rye treatment at RIO was lower than the other treatments in the August sampling period (Figure 40). It is possible that the rapidly growing rye was able to pull moisture from deeper in the profile in the early spring and make it available at shallower depths following herbicide termination of the rye in mid-May.

Fouli et al. (2012) studying components of soil water balance found deep rooted crops such as alfalfa (*Medicago sativa* L.) to have the lowest subsoil VMC compared to more shallow-based crops such as winter rye and corn in dry summers (i.e., half the normal precipitation).

Established Switchgrass: Frequency

Excluding the failed August seeding from the analysis, switchgrass frequency was not different between the rye and fallow treatments (73 and 70%, respectively; $P < 0.1801$). Frequency was lower at SC-I than at other sites but well above the 40% level. However, due to tremendous seeding year weed pressure and drought the following year, switchgrass frequency was only 20% at SC-II in 2011.

Established Switchgrass: Production

Second year yields were lower than those reported in the central and southern United States (Vogel et al., 2002, Fike et al., 2006) and quite variable, averaging 6.8 Mg ha^{-1} ± 4.2 (SD) across environments. Similar results were reported by Madakadze et al. (1999), and Wullschleger et al. (2010), with mean switchgrass yields of 8.7 ± 4.2 Mg ha^{-1} for “upland type” cultivars across the United States and eastern Canada. Of the cultivars evaluated, cultivar Cave-in-Rock exhibited exceptional high yield variability. We found no lingering effect of the previous crop history on second year production overall ($P < 0.3836$) but analysis of BLUPs did show that yields were equal or higher in the two-cut system in five of the seven environments (Figure 41).

The two environments where the one-cut harvest management resulted in significantly higher yields was due to the June harvest being accomplished later than targeted. Switchgrass sensitivity to frequent or intensive defoliation has been reported, but researchers in Iowa and Missouri found that harvesting it in mid-June during stem elongation was not detrimental to productivity (George and Oberman 1989; Anderson and Matches, 1983). Furthermore, management practices should be performed so that harvest is not delayed beyond boot stage as switchgrass advances quickly from “boot” to more sensitive reproductive growth stages. Regrowth can also be delayed when harvested past boot stage as photosynthetic material is removed.

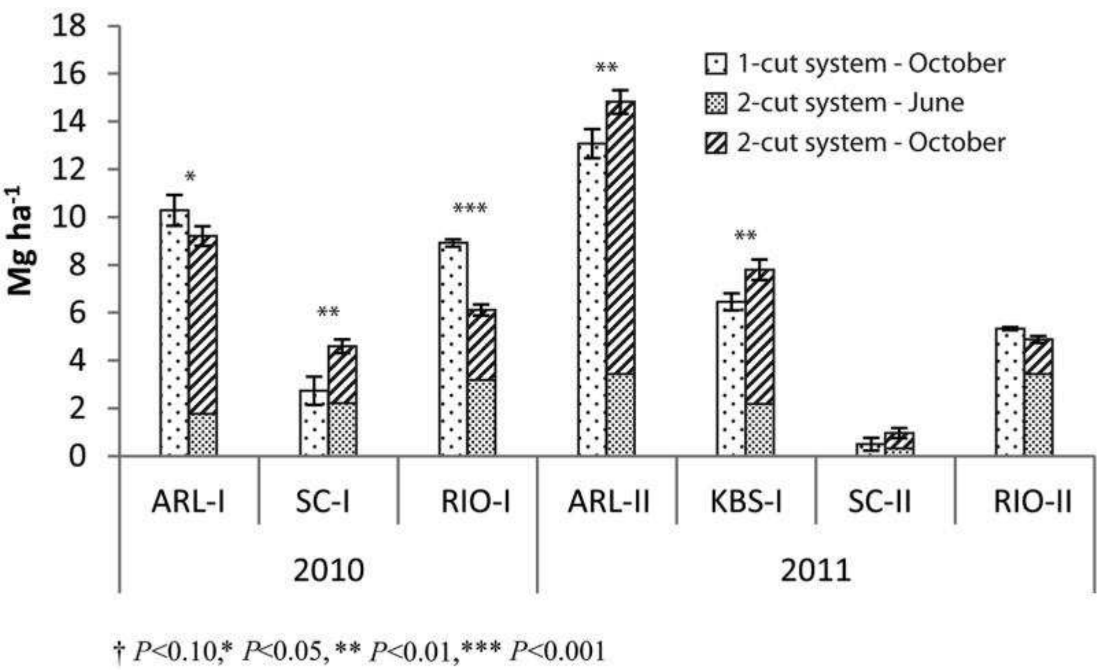


Figure 41. Second year switchgrass yields at each of the seven environments. Values represent the mean of four replicates, and error bars represent 1 standard error of the mean.

Double-Cropping and Dual-Use Cropping Systems

A positive yield response to multiple cut management systems have been reported by others for upland switchgrass varieties, including trials in Iowa, Nebraska, and throughout the southern United States (Vogel et al., 2002; Fike et al., 2006). Fike et al. (2005) report a 38% increase in yield, as well as, higher tiller density for Cave-in-Rock switchgrass under a two-cut vs. a one-cut system. In the current study we found that the two-cut system performed as well as or better than the one-cut system in five of the seven environments supporting the finding of others. We did find a significant harvest × previous crop interaction ($P < 0.0288$). This was primarily due to higher yields following fallow than rye in the two-cut system, with no effect of previous crop in the one-cut system.

In addition to cellulosic biomass there is an additional and important livestock feed component to the multi-cut forage system. Winter rye yields harvested in May at boot stage averaged 4.6 Mg ha^{-1} (ranged from 2.45–5.38 Mg ha^{-1}) with acceptable forage quality for most classes of livestock (McCormick et al., 2006). First-cut hay forage from the switchgrass harvested at boot stage (late June) yielded 2.2 to 2.5 Mg ha^{-1} and provided on average124.5 (4.1), 614.4 (5.7), 604.7 (14.9), and 16.7 (0.4) g kg^{-1} of crude protein, neutral detergent fiber (NDF), NDF-digestibility, and K, respectively (numbers in parentheses = 1 standard error). These parameters are similar to a commonly used forage in dairy systems such as orchardgrass (*Dactylis glomerata* L.; Hedtcke et al., 2011) and will satisfy the requirements of many classes of livestock including dry beef cows, gestating beef heifers, lactating beef cows (producing <14 kg milk d^{-1}), and ewes (*Ovis aries*) (Buchanan-Smith et al., 2000; Mitchell et al., 2001). Combining the total forage accumulation over the course of the present study, using winter rye before switchgrass seeding, and taking a June hay harvest in established switchgrass resulted in total biomass over 11.2 Mg DM ha^{-1} an increase of more than 38% compared to systems without rye forage.

The cost of switchgrass establishment is considerable relative to other forage crops. At present, switchgrass seed is substantially more expensive than typical forage grass and legume seed, and the slow establishment of switchgrass means that producers must forego a year of production before they have a harvestable stand. The federal Biomass Crop Assistance Program created in the 2012 farm bill covers 75% of establishment costs including seed, land preparation, and planting (Stubbs, 2011). During this study, total establishment costs were $120 per Mg of dry matter, three times higher than the establishment costs for a cool-season grass such as orchardgrass.

Biomass Quality and Theoretical Ethanol Yield

Harvested switchgrass biomass averaged 220 g ethanol kg^{-1} DM. The previous crop, rye or fallow, did not have an effect on the biomass quality for ethanol production ($P = 0.1261$). However, harvest timing did have a significant effect on biomass quality ($P < 0.001$). In the ARL-I, ARL-II, and KBS-I environments, biomass harvested after the killing frost was of higher quality for ethanol production than the biomass harvested in mid-to-late June. June-harvested biomass had high CP and low NDF contents sufficient for livestock feed, but inadequate for use as an ethanol feedstock. Energy conversion technologies favor biomass with low CP and high NDF concentrations found in late season harvests (Sanderson et al., 1999). The concentration of inorganic elements, also undesirable in ethanol production, decrease in switchgrass biomass as it matures (Adler et al., 2006). As the concentration of inorganic elements is reduced, lignocellulose constitutes a greater proportion of the biomass. During conversion, lignocellulose is broken down into simple sugars for fermentation. The late harvested biomass contained a higher concentration of lignocellulose and therefore, sugars. The translocation of nutrients, such as N, from aboveground biomass can serve the dual purpose of increasing biomass quality for ethanol conversion, and conserving key soil nutrients (Mulkey et al., 2006).

Across all environments, biomass quality did not differ between the late harvested biomass in the one-cut management system and the late harvested biomass in the two-cut management system (P = 0.2204). In addition, harvesting switchgrass as a mid-season forage did not affect the quality of biomass harvested for use in ethanol production when compared to the post-frost harvested biomass (Figure 42). Although switchgrass regrowth composition was not tested in our study, Sanderson et al. (1999) determined that CP and NDF concentrations of switchgrass regrowth were similar to concentrations observed in switchgrass harvested just once after a killing frost. It is therefore reasonable to expect a two-cut forage and biomass system to provide adequate livestock nutrition and quality biomass for ethanol conversion.

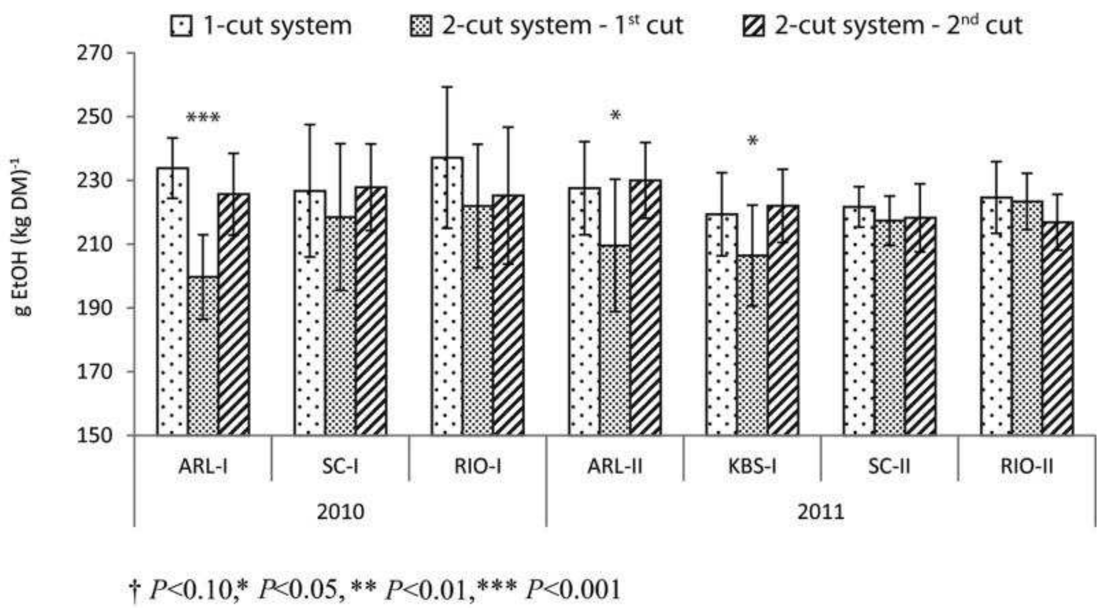


Figure 42. Biomass quality for ethanol production at seven environments across four reps and two previous crop (i.e., rye or fallow) treatments. Values represent the mean of four replicates, and error bars represent one standard error of the mean.

Although biomass quality is an important aspect of ethanol production, potential ethanol yields were more heavily dependent on the amount of biomass harvested than the composition of the biomass. Potential ethanol yields mirrored the results of second year switchgrass yields. Ethanol yields ranged from 136 L ha^{-1} at SC-II (<1 Mg DM ha^{-1} in the one-cut system) to 4225 L ha^{-1} at ARL-II (>15 Mg DM ha^{-1} in the two-cut system). Although there was no significant main effect of treatment (on-cut vs. two-cut) on total ethanol yields, analysis by environment indicated a high degree of variability among sites with significantly higher ethanol yield in two of the seven environments for each of the harvest systems (Figure 43). Again these results indicate the tight correlation between total ethanol yield and biomass yields, as environments with lower fuel yields in the two cut system were also those with lower total biomass in the two cut system (ARL-I and RIO-I, Figures 41 and 43).

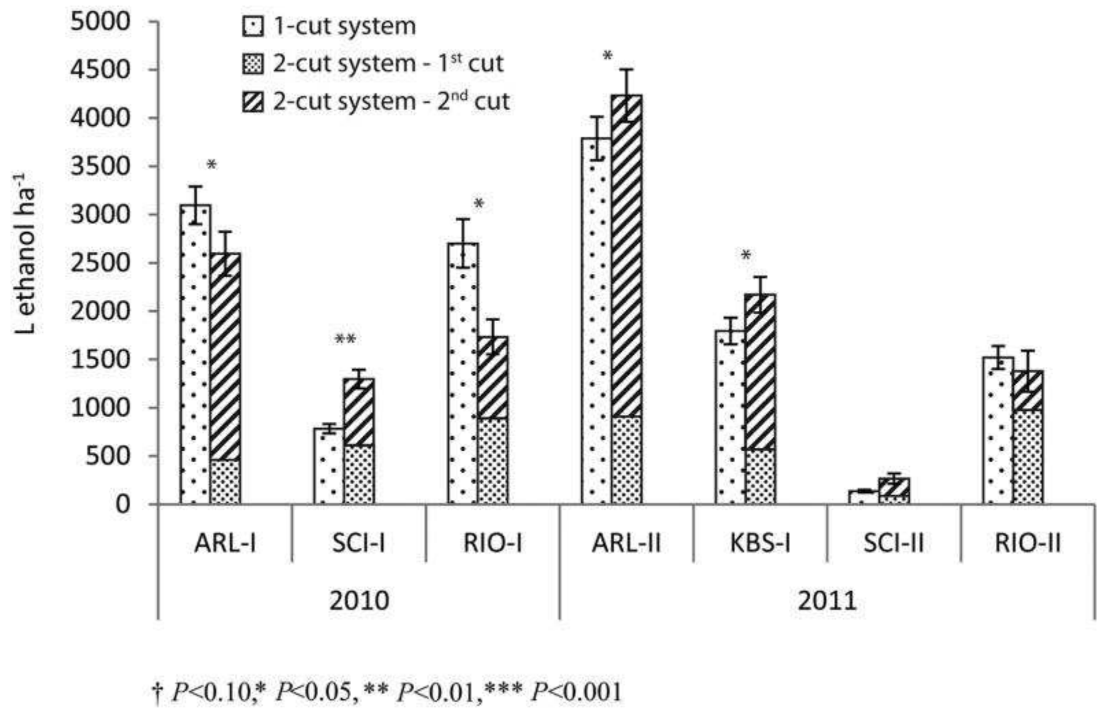


Figure 43. Potential ethanol yield at seven environments across four reps and two previous crop (i.e., rye or fallow) treatments. Values represent the mean of four replicates, and error bars represent one standard error of the mean.

CONCLUSION

Planting switchgrass in June was successful following a winter rye forage crop. Planting after winter wheat in August was not however, with significant stand loss observed. The rye forage crop did not have a negative effect on switchgrass production in either the seeding year or in the first established year and seemed to conserve soil moisture in dry years. While harvested biomass in a two-cut system was equal to or greater than that realized in a one-cut system, biomass quality for ethanol production was highest following a killing frost. In spite of this result, the higher yield in the two-cut system compensated for the lower biomass quality in overall ethanol production. Furthermore forage quality in the first cut of the two-cut system was sufficient to meet the dietary needs of several important classes of livestock. Harvesting established switchgrass for hay with an early season cutting in a two-cut system provides producers with an alternative forage source while not affecting total seasonal biomass yield if harvested at the appropriate growth stage and cutting height to leave the sufficient photosynthetic material for regrowth.

ACKNOWLEDGEMENTS

This work was funded in part by USDA-ARS Specific Cooperative Agreement 58-3655-8-692 with the University of Wisconsin-Madison and by the DOE Great Lakes Bioenergy Research Center (DOE BER Office of Science DE-FC02-07ER64494) and DOE OBP Office of Energy Efficiency and Renewable Energy (DA-AC05-76RL01830). Research technician Todd Martin assisted with the KBS site and John Hall and Nicole Tautges assisted with the experiment at the Wisconsin sites.

CHAPTER 2 NOTE

Although I am not listed as the lead author or co-author, I contributed a significant amount to this published paper. During my first year as a graduate student, I contributed:

i. writing parts of various sections, including but not limited to, a large portion of the introduction

ii. stand frequency and quadrat harvests field work and data for the second year at the KBS location

iii. entire section on theoretical ethanol yield (data acquisition, data analysis, results section)

iv. statistical analysis for the entire study with the exception of soil moisture content

v. biomass quality (as it pertained to ethanol production, not the livestock feed section) analysis

For these reasons, I have included this previously published paper as a complete chapter in my thesis.

APPENDIX

APPENDIX

Table 21. License agreement for article reprint.

ACSESS-Alliance of Crop, Soil, and Environmental Science Societies LICENSE TERMS AND CONDITIONS	
Apr 03, 2014	
This is a License Agreement between Katherine E Hadley ("You") and ACSESS-Alliance of Crop, Soil, and Environmental Science Societies ("ACSESS-Alliance of Crop, Soil, and Environmental Science Societies") provided by Copyright Clearance Center ("CCC"). The license consists of your order details, the terms and conditions provided by ACSESS-Alliance of Crop, Soil, and Environmental Science Societies, and the payment terms and conditions.	
All payments must be made in full to CCC. For payment instructions, please see information listed at the bottom of this form.	
License Number	3361531363003
License date	Apr 03, 2014
Licensed content publisher	ACSESS-Alliance of Crop, Soil, and Environmental Science Societies
Licensed content publication	Agronomy Journal
Licensed content title	Maximizing Land Use during Switchgrass Establishment in the North Central United States
Licensed copyright line	Copyright ©2014 by the American Society of Agronomy, Inc.
Licensed content author	Janet L. Hedtcke, Gregg R. Sanford, Katherine E. Hadley, et al.
Licensed content date	Mar 4, 2014
Volume number	106
Issue number	2
Type of Use	Thesis/Dissertation
Requestor type	Author of requested content
Format	Print, Electronic
Portion	chapter/article
Rights for	Main product
Duration of use	0 - 5 years
Creation of copies for the disabled	no
With minor editing privileges	no
For distribution to	United States
In the following language(s)	Original language of publication
With incidental promotional use	no
The lifetime unit quantity of new product	0 to 499

Table 21. (cont'd)

The requesting person/organization is:	Katherine E Hadley
Order reference number	
Title of your thesis / dissertation	Life-Cycle Assessment of the GLBRC Bioenergy Cropping System / Maximizing Land Use for Bioenergy Feedstock Production
Expected completion date	May 2014
Estimated size (number of pages)	150

REFERENCES

REFERENCES

Albersheim, P., D.J. Nevins, P.D. English, and A. Karr. 1967. A method for the analysis of sugars in plant cell wall polysaccharides by gasliquid chromatography. Carbohydr. Res. 5:340–345. doi:10.1016/S0008-6215(00)80510-8

Adler, P.R., M.A. Sanderson, A.A. Boateng, P.J. Weimer, and H.G. Jung. 2006. Biomass yield and biofuel quality of switchgrass harvested in fall or spring. Agron. J. 98:1518–1525. doi:10.2134/agronj2005.0351

Anderson, B., and A.G. Matches. 1983. Forage yield, quality, and persistence of switchgrass and caucasian bluestem. Agron. J. 75:119–124. doi:10.2134/agronj1983.00021962007500010030x

AOAC. 2008. Method 985.01. Metals and other elements in plants. AOAC, Gaithersburg, MD. http://eoma.aoac.org/methods/info.asp?ID=31360 (accessed 20 Aug 2013).

Buchanan-Smith, J., L.L. Berger, C. Ferrell, D.G. Fox, M. Galyean, D.P. Hutcheson, et al. 2000. Nutritional requirements of beef cattle. 7th revised ed. Natl. Academy of Sci., Washington, DC.

Fike, J.H., D.J. Parrish, D.D. Wolf, J.A. Balasko, J.T. Green, Jr., M. Rasnake, and J.H. Reynolds. 2006. Switchgrass production for the Upper Southeastern USA: Influence of cultivar and cutting frequency on biomass yields. Biomass Bioenergy 30:207–213. doi:10.1016/j.biombioe.2005.10.008

Foster, C.E., T.M. Martin, and M. Pauly. 2010. Comprehensive compositional analysis of plant cell walls (lignocellulosic biomass) Part I: Lignin. J. Vis. Exp. 37, e1745. http://www.jove.com/video/1745/comprehensivecompositional-analysis-plant-cell-walls-lignocellulosic (accessed 20 Jan. 2014). doi:10.3791/1745

Fouli, Y., S.W. Duiker, D.D. Fritton, M.H. Hall, J.E. Watson, and D.H. Johnson. 2012. Double cropping effects on forage yield and the field water balance. Agric. Water Manage. 115:104–117. doi:10.1016/j.agwat.2012.08.014

Gbur, E.E., W.W. Stroup, K.S. McCarter, S. Durham, L.J. Young, M. Christman et al. 2012. Estimation and inference in linear mixed models In: E.E. Gbur, W.W. Stroup, K.S. McCarter, S. Durham, L.J. Young, M. Christman et al., editors, Analysis of generalized linear mixed models in the agricultural and natural resource sciences. ASA, CSSA, and SSSA, Madison, WI. p. 60–67.

George, J.R., and D. Oberman. 1989. Spring defoliation to improve summer supply and quality of switchgrass. Agron. J. 81:47–52. doi:10.2134/agronj1989.00021962008100010008x

Gregory, M.M., K.L. Shea, and E.B. Bakko. 2005. Comparing agroecosystems: Effects of cropping and tillage patterns on soil, water, energy use and productivity. Renewable Agric. Food Sys. 20:81–90. doi:10.1079/RAF200493

Haramoto, E.R., and D.C. Brainard. 2012. Strip tillage and oat cover crops increase soil moisture and influence N mineralization patterns in cabbage. HortScience 47:1596–1602.

Hedtcke, J., J.L. Posner, W. Coblentz, J. Hall, R. Walgenbach, and J. Davidson. 2011. Orchardgrass ley for improved manure management in Wisconsin: II. Nutritive value and voluntary intake by dairy heifers. Agron. J. 103:1106–1114. doi:10.2134/agronj2011.0054

Hoshikawa, K. 1969. Underground organs of the seedlings and the systematics of Gramineae. Bot. Gaz. 130:192–203. doi:10.1086/336490

Hyder, D.N., A.C. Everson, and R.E. Bement. 1971. Seedling morphology and seeding failures with blue grama. J. Range Manage. 24:287–292. doi:10.2307/3896945

Jin, M.J., M.W. Lau, V. Balan, and B.E. Dale. 2010. Two-step SSCF to convert AFEX-treated switchgrass to ethanol using commercial enzymes and Saccharomyces cerevisiae 424A(LNH-ST). Bioresour. Technol. 101:8171–8178. doi:10.1016/j.biortech.2010.06.026

Joyce, B.A., W.W. Wallender, J.P. Mitchell, L.M. Huyck, S.R. Temple, P.N. Brostrom, and T.C. Hsiao. 2002. Infiltration and soil water storage under winter cover cropping in California's Sacramento Valley. Trans. ASAE 45:315–326. doi:10.13031/2013.8526

Krueger, E.S., T.E. Ochsner, P.M. Porter, and J.M. Baker. 2011. Winter rye cover crop management influences on soil water, soil nitrate, and corn development. Agron. J. 103:316–323.

Laboski, C.A.M., and J.B. Peters. 2012. Nutrient application guidelines for field, vegetable, and fruit crops in Wisconsin. Publ. A2809. UW-Madison Ext., Madison, WI. www.soils.wisc.edu/extension/pubs/A2809.pdf (accessed 20 Aug. 2013).

Lal, R., G.F. Wilson, and B.N. Okigbo. 1979. Changes in properties of an Alfisol produced by various crop covers. Soil Sci. 127:377–382. doi:10.1097/00010694-197906000-00009

Lau, M.W., and B.E. Dale. 2009. Cellulosic ethanol production from AFEXtreated corn stover using Saccharomyces cerevisiae 424A(LNHST). Proc. Natl. Acad. Sci. USA 106:1368–1373. doi:10.1073/pnas.0812364106

Littell, R.C., G.A. Milliken, W.W. Stroup, R.D. Wolfinger, and O. Schabenberger. 2006. SAS® for mixed models. 2nd ed. SAS Inst., Cary, NC.

Madakadze, I.C., K.A. Stewart, P.R. Peterson, B.E. Coulman, and D.L. Smith. 1999. Cutting frequency and nitrogen fertilization effects on yield and nitrogen concentration of switchgrass in a short season area. Crop Sci. 39:552–557. doi:10.2135/cropsci1999.0011183X003900020041x

McCormick, J.S., R.M. Sulc, D.J. Baker, and J.F. Beurerlein. 2006. Yield and nutritive value of autumn-seeded winter-hardy and winter-sensitive annual forages. Crop Sci. 46:1981–1989. doi:10.2135/cropsci2006.0140

McLaughlin, S.B., D.G. De La Torre Ugarte, C.T. Garten Jr, L.R. Lynd, M.A. Sanderson, V.R. Tolbert, and D.D. Wolf. 2002. High-value renewable energy from prairie grasses. Environ. Sci. Technol. 36:2122–2129. doi:10.1021/es010963d

McLaughlin, S.B., and M.E. Walsh. 1998. Evaluating the environmental consequences of producing herbaceous crops for bioenergy. Biomass Bioenergy 14:317–324. doi:10.1016/S0961-9534(97)10066-6

Mitchell, R.B., J. Fritz, K. Moore, L. Moser, K.P. Vogel, D. Redfearn, and D. Wester. 2001. Predicting forage quality in switchgrass and big bluestem. Agron. J. 93:118–124. doi:10.2134/agronj2001.931118x

Mitchell, R.B., K.P. Vogel, and G. Sarath. 2008. Managing and enhancing switchgrass as a bioenergy feedstock. Biofuels Bioprod. Bioref. 2:530–539. doi:10.1002/bbb.106

Monti, A., editor. 2012. Switchgrass: A valuable biomass crop for energy. Springer-Verlag Publ., London, UK.

Moore, K.J., L.E. Moser, K.P. Vogel, S.S. Waller, B.E. Johnson, and J.F. Pedersen. 1991. Describing and quantifying growth stages of perennial forage grasses. Agron. J. 83:1073–1077. doi:10.2134/agronj1991.00021962008300060027x

Mulkey, V.R., V.N. Owens, and D.K. Lee. 2006. Management of switchgrass-dominated conservation reserve program lands for biomass production in South Dakota. Crop Sci. 46:712–720. doi:10.2135/cropsci2005.04-0007

Renz, M., D.J. Undersander, and M.D. Casler. 2009. Establishing and managing switchgrass. UW-Madison Ext., Madison, WI. www.uwex.edu/ces/forage/pubs/switchgrass.pdf (accessed 20 Aug. 2013).

Sanderson, M.A., J.C. Read, and R.L. Reed. 1999. Harvest management of switchgrass for biomass feedstock and forage production. Agron. J. 91:5–10. doi:10.2134/agronj1999.00021962009100010002x

Sanderson, M.A., and R.L. Reed. 2000. Switchgrass growth and development: Water, nitrogen, and plant density effects. J. Range Manage. 53:221–227. doi:10.2307/4003287

Sanderson, M.A., M. Schmer, V. Owens, P. Keyser, and W. Elbersen. 2012. Crop management of switchgrass. In: A. Monti, editor, Switchgrass: A valuable biomass crop for energy. Springer-Verlag Publ., London, UK. p. 88–90.

SAS Institute. 2006. 1.3 User's guide: Statistics. Vol. 9. SAS Inst., Cary, NC.

Schmer, M.R., K.P. Vogel, R.B. Mitchell, L.E. Moser, K.M. Eskridge, and R.K. Perrin. 2006. Establishment stand thresholds for switchgrass grown as a bioenergy crop. Crop Sci. 46:157–161. doi:10.2135/cropsci2005.0264

Schulte, E.E., J.B. Peters, and P.R. Hodgson. 1987. Wisconsin procedures for soil testing, plant analysis and feed and forage analysis. Dep. of Soil Sci. Bull. 6. Univ. of Wisconsin, Madison.

Selvendran, R.R., and M.A. O'Neill. 1987. Isolation and analysis of cell walls from plant material. Methods Biochem. Anal. 32:25–153. doi:10.1002/9780470110539.ch2

Stubbs, M. 2011. Biomass Crop Assistance Program (BCAP): Status and issues. Congressional Res. Serv. 7-5700. R41296. www.fas.org/sgp/crs/misc/R41296.pdf (accessed 11 Nov. 2013).

Troeh, F.R., J.A. Hobbs, and R.L. Donahue. 2004. Soil and water conservation: For productivity and environmental protection. 4th ed. Pearson Education, Inc., Upper Saddle River, NJ.

Unger, P.W., and M.F. Vigil. 1998. Cover crop effects on soil water relationships. J. Soil Water Conserv. 53:200–207.

Updegraff, D.M. 1969. Semimicro determination of cellulose in biological materials. Anal. Biochem. 32:420–424. doi:10.1016/S0003-2697(69)80009-6

USDA-ERS. 2013. Bioenergy: Findings. USDA-Economic Res. Serv. www.ers.usda.gov/topics/farm-economy/bioenergy/findings.aspx#.UhTyt-5I3ukF (accessed 21 Aug. 2013).

USDA-SARE. 2013. 2012–2013 cover crop survey. USDA-Sustainable Agric. Res. and Educ. www.northcentralsare.org/Educational-Resources/From-the-Field/Cover-Crops-Survey-Analysis. (accessed 20 Aug. 2013).

U.S. Department of Energy. 2011. U.S. Billion-ton update: Biomass supply for a bioenergy and bioproducts industry. R.D. Perlack and B.J. Stokes, editors, ORLN/TM-2011/224. Oak Ridge Natl. Lab., Oak Ridge, TN. www1.eere.energy.gov/bioenergy/pdfs/billion_ton_update.pdf (accessed 20 Aug. 2013).

Vogel, K.P. 2004. Switchgrass. In: L.E. Sollenberger, L. Moser, and B. Burson, editors, Warm-season (C4) grasses. Agron. Monogr. 45. ASA, CSSA, and SSSA, Madison WI.

Vogel, K.P., J.J. Brejda, D.T. Walters, and D.R., Buxton. 2002. Switchgrass biomass production in the Midwest USA: Harvest and nitrogen management. Agron. J. 94:413–420.

Vogel, K.P., and R.A. Masters. 2001. Frequency grid–A simple tool for measuring grassland establishment. J. Range Manage. 54:653–655. doi:10.2307/4003666

Wullschleger, S.D., E.B. Davis, M.E. Borsuk, C.A. Gunderson, and L.R. Lynd. 2010. Biomass production in switchgrass across the United States: Database description and determinants of yield. Crop Sci. 102:1158–1168.